1 An introduction to quantified eco-efficiency analysis

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1.1 The challenge of sustainability

A growing global population with growing affluence may well lead to reduced environmental quality and a diminishing quality of nature, ultimately jeopardizing the quality of human life and even human life itself. The challenge we face is to reduce the environmental consequences of our actions so as to reduce environmental risks and to retain the quality of the environment not only as is necessary for survival but also reflecting higher order values on nature and human life, as for example reflected in the concept of sustainability. The challenge has down to earth properties. Environmental impacts per unit of welfare, as eco-efficiency, on average should be appropriate for sustainability. Simplifying the analysis a bit, as by disregarding non-linearities and dynamics, in any year the total amount of environmental impacts should be within limits as set by sustainability considerations. In any one year this total amount is the sum-total of all micro-level economic actions in production, consumption and waste management, including investments and public sector activities. These economic actions grow in real terms, for the decades to come may be by four percent per year. Therefore, the eco-efficiency requirements on global society as a whole somehow have to be matched by eco-efficiency requirements on all our activities to counteract such expected growth. They should be reflected in all our economic decisions.

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There is no direct correspondence to micro level actions and decisions, however. The average macro level environmental burden per unit of expenditure, actual or allowable, cannot be matched with environmental impact per unit of value added in a micro level activity. Some activities by nature can be virtually without environmental impact, as in many cultural events like singing classes or mathematics studies. Other activities, like international travel and coal mining, have a high impact per unit of value added by shear technical necessity. Putting the same eco-efficiency requirement on all activities as is valid on average at a macro level clearly is not possible. Still, in order to reach the required eco-efficiency at macro level, that is the sum of our micro level actions in terms of value and environmental impact, there should be requirements on individual activities and decisions. Before engaging in the difficult and by nature political process of *who should do what* to safeguard our future, we first should know the empirical facts and developments: what is the eco-efficiency of our current activities, how do they develop and which options for further improving eco-efficiency do we have. Though statistically the macro level just is the sum of all micro level activities, the link to decision making is not so clear. Individual economic actions are not created in a void but are intricately related. Reducing emissions at one spot may well lead to more than compensating increases in other spots, as might be the case with bio-ethanol from grain in gasoline (Farrell et al. 2006). Production and consumption chains, and their waste management requirements, are intricately related and may cover many years as with investment goods and durable consumer goods. So the unit of decision making cannot just be individual activities, as their interrelations have to be taken into account. This leads to modeling of interrelations in developing product systems, of firms behavior, of regions and countries, with all complex feedback loops as are present in society. Eco-efficiency analysis of decisions depends on such models, simple or complex. Only for monitoring purposes, eco-efficiency analysis does not pertain to effects of decisions and actions, but to the environmental impacts and value created by activities which can be added to a yearly total for the world. The units to add up ultimately are single activities, however defined, and aggregates of these. Examples are firms; private consumption households; sectors; regions; and product systems. Only for very simple models the link to the macro level is relatively direct, as with environmentally extended input-output analysis. Also steady state type LCA is close, related to the requirement that the sum of all parts is the total, but still abstracts from the fact that actual product system cover a time span of many years or even decades.

As a next step, still not really normative and political, we may ask questions on optimality. Can we distinguish options as being either superior or inferior, as when a product is dominant in decision making terminology, having the same functionality with lower cost and with lower environmental impact than also available alternatives? Limited value judgments may suffice here. A choice for an option with the same value and lower environmental impact, or higher value with same environmental impact, is generally to be preferred. Based on such minimal Pareto-like assumptions, quantified eco-efficiency analysis already can give guidance on choices regarding technology and consumption. As one part of the macro equation, population growth, is hardly amenable to policy, at least not in the time frame of decades, and as rising global affluence is globally accepted as a central aim of public policies, we will have to look at the other part of the equation, the environmental impact per unit of welfare, shifting technologies of production and consumption in a sustainable direction. This discussion is has the same background as the Factor X discussion, but focuses on the precise nature of what constitutes the nominator and denominator in this Factor. That question boils down to how to measure eco-efficiency empirically and how to measure its development.

So, in this paper eco-efficiency analysis firstly is an instrument for sustainability analysis, primarily indicating an empirical relation in economic activities between environmental cost or value and environmental impact. This empirical relation can be matched against normative considerations as to how much environmental quality or improvement society would like to offer in exchange for economic welfare, or what the trade-off between the economy and the environment should be if society is to realize a certain level of environmental quality. Its relevance lies in the fact that relations between economy and environment are not self-evident, not at a micro level and not at the macro level resulting from micro-level decisions for society as a whole. Clarifying the why and what of eco-efficiency is a first step towards decision support on these two aspects of sustainability. With the main analytic framework established, filling in the actual economic and environmental relations requires further choices in modeling. Also, the integration of different environmental effects into a single score requires a clear definition of approach, because several partly overlapping methods exist. Some scaling problems accompany the specification of numerator and denominator, which need a solution and a certain amount of standardization is required before eco-efficiency analysis can become more widely used. With a method established, the final decision is how to embed it in practical decisionmaking. In getting the details of eco-efficiency better specified, its strengths, but also its weaknesses and limitations, need to be indicated more clearly.

Eco-efficiency as a subject is well established but diverse, or rich if we want to emphasize the positive side of this diversity. The richness not only stems from different terminologies developed in different domains involved (Huppes and Ishikawa 2005), but also from more basic, underlying theoretical approaches to this integrative subject. One might avoid the cumbersome details of explicit modeling and evaluation as advocated in this article and go for direct practical solutions, as advocated by Seiler-Hausmann and colleagues (2004) and Bleischwitz and Hennicke (2004). Solutions then relate to management approaches and strategies, using material flow analysis (MFA), and developing sets of sustainability indicators, all depending on the situation. This, of course, is useful and necessary but does not answer the question of what is to be achieved by the management strategies, in terms of economic and environmental goals, and combined as eco-efficiency. We prefer to keep separate the empirical analysis; the evaluation; and the drivers of sustainability, as suggested by Ekins (2005). So, before arriving at solutions, the basic question remains: why eco-efficiency? Does not society have enough environmental quality standards and quality goals, and instruments to realize them, if only enough political will were present? The answer clearly is ‘no’. For policy development, political opinion formation, and well-considered private action, an integrated view, translated into well-defined methods and procedures for weighing economic and environmental aspects, is lacking. Without them, it is difficult to say what is good, not so good, and very good, beyond the simple situation where environmental improvement is possible without cost and without side effects. So we first go into the why question, with answers suggesting that it is important to begin by being more precise on the what, that is, the subject to which eco-efficiency is referring. With the why and the what established, the how questions remain: how to quantify the economic part and the environmental part of the eco-efficiency score, and how to combine these scores into the desired eco-efficiency ratio, where some scaling problems arise. The final framework subject is how to link the analysis to applications, the proof of the pudding. We indicate a few main lines of thought, referring to policies, investment decisions, and product and installation design and development.

1.2 Eco-efficiency for sustainability

Sustainability refers to reconciling environmental, economic and social concerns both from a current point of view and long term intergenerational perspective. Making the jump from concept to tool is loaded with ethical-normative and practical modeling complexities, which cannot be resolved in a broadly acceptable way. Different opinions exist, for example, on the exchanges allowable between the economic and the ecological domain, reflected in positions on (very) strong to (very) weak sustainability (see Neumayer 2003). Eco-efficiency analysis as advocated here does not take a stance on such issues but tries to straighten out the underlying empirical analysis which may show that we are on a path of very strong or of very weak sustainability. To be open to such different options it is essential not to aggregate environmental and economic aspects, but leave them as separate entities as one input into the discussion on strong versus weak sustainability. However, in using eco-efficiency analysis for practical decision support at a micro level of specific firms, products and technologies, and for policies related to these, some link to an encompassing concept of sustainability has to be established, as limited as possible to be open to different positions, but allowing for some broadly agreed upon practical guidance. In simple situations, choices may be clear as when between two options one is superior both in environmental and in economic terms. A simple dominance analysis then suffices. However, in practice such situations are limited and usually some trade-off between economy and environment is involved. Guidance on the trade-off can be given based on broadly accepted assumptions. There is broad support for the position that economic growth should not lead to a deteriorating environmental quality, reflecting a *not-so-strong sustainability* point of view.

1.3 Eco-efficiency, economic growth and Factor X

The simple fact is that quantified eco-efficiency is needed is for analyzing the micro level conditions for simultaneous satisfaction of the rising consumption of a growing global population and attainment of reasonable environmental quality. Spoiling the environment for no good reason seems foolish. But whether we are foolish as a society - or better, how foolish we are - is difficult to tell if there is no method for answering the right questions in this respect. It is not one question that is to be answered, such as “how high is our eco-efficiency?” The real question is how society can support a high standard of living with a high environmental quality, with several questions related, of which a number refer to eco-efficiency, both at a micro and macro level. Discussion of effectiveness of actions, in terms of a certain quality of the environment to be reached at a macro level, and the eco-efficiency of measures at a micro level, which is related to that environmental goal but not in a direct way, has been long-standing. One may take a series of relatively eco-efficient micro-level measures, and even improve their eco-efficiency in time, but never arrive at the desired or required environmental quality; see, for example, the arguments of McDonough and Braungart (2001). Economic growth eats away the improvements per unit of consumption. One may therefore leave the realm of eco-efficiency and - seemingly - pursue effectiveness in a more direct way, as has been done in the past in the Factor X discussion, for example, realizing a Factor Ten improvement in all products in 40 years time (Factor 10 Manifesto, p. 13). This sounds impressive, corresponding to an improvement in environmental impact per unit of product of 6% per year. However, a rise in consumption by 4% per year may reduce the Factor Ten effect substantially, leaving only a Factor Two in 40 years time. If, in this same period, rising affluence leads to consumption shifts in an environmentally more stressing directions, for example, more traveling, more meat consumption, and more air conditioning, the net environmental effectiveness may well be negative despite realizing Factor Ten in all products. The effectiveness-related objections to eco-efficiency seem to miss the point that it is not the concept that is wrong but the eco-efficiency improvements at a micro level that are quantitatively insufficient for reaching the environmental quality goal at a macro level. Trying to link the micro level directly to the macro level seems an inappropriate route; macro level developments play their independent role. Because the eco-efficiency concept can be applied at the macro-level as well, to regions and countries, some of the discussion of effectiveness is part of the eco-efficiency analysis, such as analyzing the eco-efficiency of recycling in a region (see Morioka et al. 2005 and Seppälä et al. 2005).

So let us get back to the ultimate problem faced by society: Economic growth is increasing in large parts of the world and environmental assets are fading fast, globally. The Millennium Ecosystem Assessment (2005) has shown that a sad deterioration of all major environmental assets was taking place in the world even before economic growth in China and India picked up to current high levels. In many instances the scientists involved see no good reason at present for a reversal of such downward trends, because the drivers of these developments are the aspirations of all global citizens to become affluent, and firms and governments set a high priority on accommodating those wishes. Even the richest Western societies strive for more and more, because there is no real limit to demand, and working more may enhance international competitiveness. Without taking this desire for granted, it must be accepted that some level of growth will be present for a long time to come, not only driven by demand but also by R&D and resulting technological advances on the supply side. If economic growth cannot be redirected substantially into an environmentally benign direction, the trends of the Millennium Assessment are unavoidable. Next, why are the simple tools of the past not applicable to the future? We have more or less solved the ozone layer depletion problem and, in the Western world, the acidification problem; why not tackle all problems like that? The answer is that in many instances, the simple banning of substances, or a limited number of end-of-pipe measures, is not an option any more. Such low hanging fruit has mainly been picked, whereas the sheer size and complexity of economic activities have risen to unprecedented levels, as part of globalization. Somehow, our globally connected actions at a micro level have to be reconciled with environmental quality at a macro level, most actions directly and indirectly having consequences for most environmental problems on earth. Therefore, the multifaceted environmental quality goal must be translated back to the level of decision making at a micro level, be it for public policies or for enlightened actions by firms and individuals. It is a requirement for such policies and actions to reconcile market-related economic welfare with the environment. One cannot hope to grasp this all in two numbers, but the nominator and denominator of eco-efficiency clearly are of central importance.

New environmental problems, such as ocean fisheries depletion, and problems not so easily linked to specific economic activities, such as global species mix, do not fit well into the eco-efficiency framework. Even if only the emissions of hazardous substances, including eutrophicating substances, could systematically be brought into the analysis, though, the simplification in decision making would be enormous, freeing regulatory power and intellectual capacity for solving other, less directly linked environmental problems, and also for solving social problems. Eco-efficiency is not only relevant for general cost considerations. At a political level, the power of the market and the urge for full employment are very strong. If, for fear of the crudeness of simplification of analysis, eco-efficiency is not defined and established, it is not so much the reduction of affluence that will result due to inefficiency, but a less effective policy and lower environmental quality. Reducing the cost of environmental improvement by increased eco-efficiency thus is a means to higher environmental quality as well. So answering the why question: leads to the what question: the eco-efficiency of what should be improved to shift society toward higher environmental quality?

1.4 Definitions of eco-efficiency

A wide variety of terminology referring to eco-efficiency has been developing, differing depending on application, on the background of the researchers, and possibly even on views on how to treat negative signs. Some autonomous divergence is also present, because subgroups involved in the discourse do not refer to each other. As a result, the term *eco-efficiency* is used in different ways and other terms are used that overlap with these meanings, such as environmental cost-effectiveness and environmental productivity. We try to bring some order into this usage, distinguishing between the formal definition and the specific content given to the variables involved. We focus on the formal definition here. The content given to cost and value, as economic categories, has been widely standardized in accounting conventions—see the publications lists of International Standards of Accounting and Reporting (ISAR 2005)—and ideally fits into the framework of national accounting as actively standardized under United Nations coordination in the System of National Accounts (SNA 2002). In analyzing the eco-efficiency of a new technology or product, however, aggregate accounting frameworks may miss essential detail and related effect mechanisms. Hence, they cannot be the last word. Management-oriented concepts such as cost-benefit analysis (see, for example, Mishan 1971 and Dasgupta and Pearce 1972, both for public applications) and life-cycle costing (see, for example, Fisher 1971 for public applications and Dhillon 1989 for private applications) may then be more appropriate for public and private applications but also lack standardization. For the environmental part, no such detailed standards exist. A great variety of theoretical and practical approaches have emerged, in parallel at best, but often overlapping. The standards for life-cycle assessment, ISO 14042, developed by the International Standards Organizations, give only a few guidelines. Work by the Society for Environmental Toxicology and Chemistry (SETAC), now incorporated into the Life-Cycle Initiative of the United Nations Environment Program and SETAC, is more detailed but has not yet led to broad acceptance of specific methods. Though it is of prime importance for the eco-efficiency discussion, we will not venture into this subject here. Here, we assume a normal, albeit complex, situation in which environmental aspects of decisions cannot be encompassed by just a single environmental intervention, such as emission of carbon dioxide (CO_2) or sulfur oxides (SO_x), but relate to a usually large group of environmental interventions. These in turn link to the environmental effects mechanisms that follow interventions, such as climate change, acidification, and summer smog formation, which in turn relate to areas of protection such as human health, ecological health, and human welfare. So more encompassing concepts are needed to represent the environmental part of eco-efficiency, which have not yet been filled in a comprehensive and broadly accepted way. Contrary to specific applications meant for eco-efficiency, as in the business orientation of the World Business Council for Sustainable Development (WBCSD), the concepts defined here are generally applicable to choices regarding both production and consumption and to choices regarding public policies and private choices, both of a practical and a strategic nature.

Eco-efficiency has been defined as a general goal of creating value while decreasing environmental impact. Leaving out the normative part of this concept, the empirical part refers to a ratio between environmental impact and economic cost or value. Two basic choices must be made in defining practical eco-efficiency: which variable is in the denominator and which is in the numerator; and whether to specify environmental impact or improvement and value created or cost. Distinguishing between two situations, the general one of value creation and the specific one of environmental improvement efforts, and leaving the numerator - denominator choice to the user, as diverging practices have developed, four basic types of eco-efficiency result: environmental intensity and environmental productivity in the realm of value creation; and environmental improvement cost and environmental cost-effectiveness in the realm of environmental improvement measures.

1.5 Choices in terminology

The starting point for the formal definition of eco-efficiency is the general definition of WBCSD (1992, 2001; an overview can be found in DeSimone and Popoff 2000), which goes back to the work of Schaltegger and Sturm (1989). They describe eco-efficiency as a ratio between two elements: environmental impact, to be reduced, and value of production, to be increased. We disregard the normative overtones again, looking at eco-efficiency as a measuring rod only. The value of production lies in the products produced, comprising both goods and services. Two equivalent variants are used, the ratio of value to environmental impact (for example WBCSD 2001) and the ratio of environmental impact to value (for example UN 2003), one being the exact inverse of the other, but with the same information content. In addition to the creation of maximum value with minimum environmental impact, there is the analysis of dedicated environmental improvements (see for example Hellweg et al. 2005). The focus then shifts from the creation of value to the reduction of cost for the environmental improvements investigated. The signs of both numerator and denominator then reverse, or the variables are defined in the opposite direction. This distinction between the analysis of value creation and the analysis of environmental improvements can be combined with the inversion options. It seems wisest to make eco-efficiency an overarching general concept, with variants residing under this umbrella.

Table 1.1 Four basic variants of eco-efficiency

	Product or production prime	*Environmental improvement prime*
Economy divided by environment	Production/consumption value per unit of environmental impact: **1 environmental productivity**	Cost per unit of environmental improvement: **3 environmental improvement cost**
Environment divided by economy	Environmental impact per unit of prodution/consumption value or: **2 environmental intensity**	Environmental improvement per unit of cost: **4 environmental cost-effectiveness**

The relationship of these variants is shown in Table 1.1. In actual applications, there often is not a full system being analyzed but a difference analysis between options is performed, with positive and negative results depending on which situation is taken as a reference. For example, in a win-win situation resulting from technological improvement, described as a difference from the current - or not improved future - situation, the denominator of environmental productivity becomes negative, as then does the ratio itself. Similarly, some environmental improvements may not entail cost but reduce cost as, for example, by creating additional value. Then the environmental cost-effectiveness becomes negative. Making separate categories also for these cases would lead to a confusingly large number of terms, because, for each of the four basic options, the sign of the numerator, of the denominator, or of both may change. If all these situations were really distinguished, 16 options would result. The reason for discerning them is that the principle of “higher (or lower) is better” does not hold any longer with a sign change, nor when absolute values are taken. It seems better to treat such situations in a practical way on a case-by-case basis. Such special cases may easily be subsumed under any of the four basic variants of eco-efficiency. Along with these four basic eco-efficiency terms and concepts, there are similar concepts, with related meanings, such as energy productivity, (primary or total) resource productivity, capital productivity, and labor productivity, with each one having the corresponding intensity as an inverse, see Heijungs (2006) in this book. As he describes, a group of terms relates to technology discourse, where there is an input-output efficiency referring to the same variable occurring both as an input and as an output, with efficiency being the complement of the loss factor. Examples are resource efficiency in kilograms/kilogram and energy efficiency, in joules/joule. The eco-efficiency terms, alas, are not in line with this technology-oriented terminology. In eco-efficiency, the environmental impacts and the economic impacts both relate mainly to outputs of the activities involved in production, consumption, and disposal management. Of course, such input-output concepts might be subsumed under the eco-efficiency umbrella, leading to additional types.

The basic terminology proposed here deviates slightly from the one used in most eco-efficiency publications, by being more encompassing and by having two levels of generality. It has the advantage that it clarifies formal meaning, while leaving specific content open to a next level of more detailed discussion. This terminology proposal is meant for easier communication. Of course a consensus on terminology requires a broader social endeavor, involving the many fora involved. Organizing the consensus-formation process is hampered by the decentralized nature of the eco-efficiency community. A cross-cutting organization such as the temporary eco-efficiency conference community resulting from focused conferences might form a most practical path.

So, summarizing, we distinguish four main types of eco-efficiency (Huppes and Ishikawa 2005). The first two are environmental productivity and its inverse, environmental intensity of production, referring to the realm of production. The second pair, environmental improvement cost and its inverse, environmental cost-effectiveness, are defined from an environmental improvement measures point of view.

1.6 Eco-efficiency of what?

Eco-efficiency, as a ratio between economic value and environmental impact, may be applied to any unit comprising economic activities, as these activities always relate to cost and value, and having some physical substrate, always influence the environment. The units may encompassing, as comprising total society, that is the macro level. Several options exist for units at a more micro level of aggregation, as involving sectors, technologies, product systems, regions and countries. We treat the micro and macro options in this order. So we first specify the eco-efficiency of products and technologies at a micro level, as in Figure 1.1, and then sketch the relation to eco-efficiency at the macro level, as in Figure 1.2. Some more detail on these micro-macro relations, such as between GDP, factor incomes, and costs of firms, may be added (Kuosmanen 2005), but is not required yet in this framework analysis. Also, the relation between value and capital is not explored, though clearly relevant in the context of intergenerational sustainability analysis, to which eco-efficiency should contribute. Figge and Hahn (2005) explore this subject and indicate that, starting at the level of economic, environmental, and social capital, the eco-efficiency of firms may be defined. Finally, we make some remarks on environmental effectiveness in a dynamic context, which is more realistic but also more complex to analyze, with elements such as sunk cost, technological lock-ins, saddle points secondary effects of decisions as in income effects and rebound effects, macroeconomic mechanisms, and political limitations. The conflict between realism and easy practicality is a central subject there.

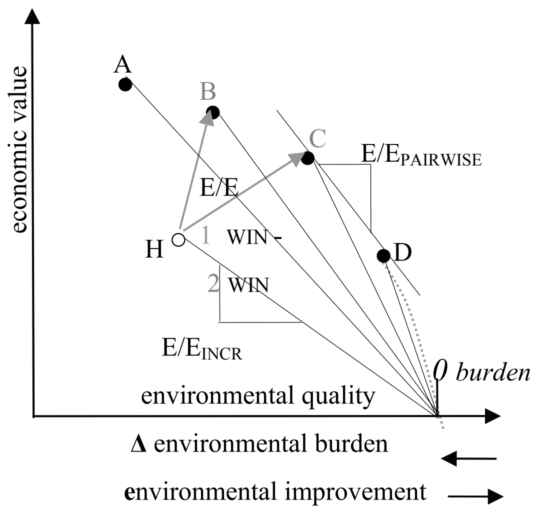

Figure 1.1 Eco-efficiency of technologies: E/E_{INCR}, $E/E_{WIN\text{-}WIN}$ and $E/E_{PAIRWISE}$. H represents a current historical reference situation and A to D are new technical options

Micro-level eco-efficiency of technologies

In Figure 1.1 we depict three basic options for applying eco-efficiency at a micro level, each with its own numerical outcomes. This figure assumes a given amount of production factors being available, with each point indicating a production possibility for society. Of course in practice a firm may opt for simplification of the optimality requirements related to the selection of production factors for application in specific activities and technologies. The first application, incremental eco-efficiency, E/E_{INCR}, specifies the effects of the total value of a product system or sector and its total concomitant environmental effects, for example, as environmental productivity. It is depicted for a number of technologies by the lines starting from zero burden. One may further differentiate within these totals by indicating the effects of one incremental unit of production. This difference of course shows only if the model can specify (dis-)economies of scale. The curved dotted line OD depicts the marginal eco-efficiency of one unit of production. As it is not short term optimization in which we are interested, the incremental technology unit E/E_{INCR} may be interpreted as long term marginal analysis, adapting all capital goods to the intended volume of production or consumption. This nonlinear analysis is hardly ever available in simple practical economy-environment models such as life-cycle assessment (LCA)-based models, which are linear homogeneous. In such models, the average score and the one-unit-incremental score are identical. For models with results depending on scale, such a shift at the boundary is very similar to comparisons between technologies A, B, and so forth; see below. To avoid a further terminological differentiation, we do not treat this as a separate option. We refer to the full market volumes here as incremental eco-efficiency and reserve the term marginal eco-efficiency for comparison between technologies; see below. The second application is $E/E_{WIN-WIN}$, which gives a comparison between a historical reference situation H and potentially new situations based on the use of improved technologies, here A to D. Options B and C then depict win-win situations. Of course if a still more inferior historical reference is chosen, to the South-West of H, more situations fall under the heading of win-win. The Factor X analysis also falls into this category, but then is not based on the monetary value of a product but on its physical units with a certain utility, as in LCA with its functional unit. The disadvantage of having an irrelevant alternative (if the old option is obsolete) as a reference is that all numerical outcomes depend on it, and hence also all eco-efficiency scores. Using such a measure in broader optimality analysis goes against the basic rule in social choice theory of independence of irrelevant alternatives (Arrow, 1970; Sen, 1970). However, it is quite handy in indicating the amount and rate of progress in specific technology development.

The usefulness of such win-win analysis hence is limited, because it cannot give guidance on the question of whether the win-win realized is good enough for society to adequately improve its overall environmental performance. For example, it may well be that win-win situation B involves an economy-environment trade-off that would be highly destructive of the environment if applied throughout society, because it leads to environmental burdens ten times higher than option D. An example might be in energy production, where shifting from coal-fired power stations, as option H, to integrated gasification combined cycle power production might constitute option B. Large scale carbon sequestration is, however, needed to reduce climate-changing emissions to desirable levels, represented by option D. The third micro-level eco-efficiency application, difference eco-efficiency or $E/E_{PAIRWISE}$, is similar to the win-win variant, as also here two alternatives are compared. But its use is totally different. First, it is applied to remove all irrelevant alternatives, that is, those lying within the concave envelope created by the most attractive options. Option H, being dominated by B and C in decision-theoretical terms, does not belong to the potentially optimum set of technologies and hence is irrelevant in decision making. When all such irrelevant alternatives have been removed, the envelope of potentially optimal technologies remains. The difference analysis between two adjoining technologies on the optimum envelope may, ideally, be transformed into a marginal analysis, indicating the trade-off at the point of that technology implied by a shift in the one or the other direction. We use the term marginal eco-efficiency for trade-offs at this optimum envelope, both for specific technology domains and for society at large. Which of the technology alternatives is actually optimal depends on how we see the trade-off between economic value (in constant prices) and environmental value, from a normative point of view. If we put a relatively low weight on environmental quality, option A becomes best, but with a high value on environmental quality option D is to be preferred, with B and C falling in between. For orthodox neo-classical economists, the units on both axes n principle are the same: utility as represented by its monetary value. Then, after such scaling, the trade-off is given as 1:1. If the axes are not in the same unit, the value choice of relative importance of economy vis-à-vis environment is to be made explicitly in order to define what is optimal, linking the two different variables involved. This is the general situation for non-orthodox economists as well. Ultimately, with all normative trade-offs defined, the non-economist and economist approaches do not differ so much, because with appropriate rescaling of the environmental axis, the trade-off per unit can be arranged to become 1:1. The basis for integration of environmental aspects into a single score may be very different, however, giving a different meaning to the outcomes. One interesting consequence of this trade-off analysis is that the difference in application to full production volumes (as in the approach to eco-efficiency used by the World Business Council on Sustainable Development - WBCSD2000) versus eco-efficiency analysis of specific environmental improvement measures (as in contributions by Scholz and Wiek (2005) and Hellweg and colleagues, 2005), as environmental cost-effectiveness, vanishes. They both are marginal eco-efficiency analysis (in the terminology used here), to be evaluated in the same marginal eco-efficiency framework as used for process- integrated alternatives. A further consequence of this analysis is that the link to macro-level analysis now can be specified in a way that connects to optimality analysis for society, which ultimately forms the broadest level of justification for eco-efficiency analysis.

Macro-level eco-efficiency of society

The ultimate aim of eco-efficiency analysis is to help move micro-level decision making into macro-level optimality. This in turn is based on the environmental quality society seeks, given a specific level of economic development, as macro-level eco-efficiency to be attained. The trade-off society makes normatively determines what is optimal, as one point on the societal production possibility curve. So the sum total of all production factors corresponds to a set of potentially optimal points on the production possibility curve (see, in this vein of thought, the work of Bator 1957). Potentially optimal points from the domain envelope, each with the same trade-off point, add up to a point at the societal envelope having that same trade-off. If in society in one domain a certain trade-off is realized and in another domain a different one, they add up to a point within the societal envelope of potentially optimal points. Hence such a point cannot itself be optimal. This leads to the for some people counterintuitive consequence: improving the environment by increasing the trade-off in a certain domain to the right downward part of the envelope, for example, building quite environmentally friendly but extremely expensive solar power installations may detract from absolute environmental quality, because welfare losses of a smaller amount could have realized larger environmental gains. Of course experimental application may be a useful part of product development, as an R&D effort.

When linking to this macro-level analysis, we assume that different studies on eco-efficiency use the same units for economic value or cost and for environmental impacts and benefits. In actual applications, this hardly ever is the case. Even if using the same impact categories, in many studies the two axes are normalized relative to some alternative or to an average of some set of alternatives, whereas others normalize only the environmental axis in such a case dependent way (Kobayashi et al. 2005; Rüdenauer et al. 2005; Suh et al. 2005). Eco-efficiency scores, seemingly comparable, then are not due to differences in scaling on the two axes. Placing the eco-efficiency analysis in a broader societal efficiency context requires a case independent specification of the axes (see work by Heijungs et al. 1992 and Norris 2001). Without having the same units on the axes for different cases, no comparable trade-offs can be quantified and an inter-case analysis becomes impossible. Applicability of eco-efficiency then reduces to specific domains of application. This still is useful for eliminating suboptimal variants at that case level but does not fit into the macro level analysis we think ultimately is required. But given the conceptual problems involved in specifying a normatively valid trade-off between environmental aspects, one can hardly expect results to have high validity at a case level now. For linking the micro level to the macro level, the starting point for adding economic and environmental effects of all technologies is a hypothetical zero-burden situation; see Figure 1.2. By simple addition, total environmental burdens of all technologies together may be related to total environmental quality, as E/E_{TOTAL}. Let us first start with an actual situation, which is such a sum-total of all actual economic activities in society. Technologies in society are added, starting from the zero-burden point, until the total production & consumption volume is covered. The lines depicting technologies indicate their contribution to economic value and environmental burden, as incremental eco-efficiency. Their total depicts the similar measure for society, as environmental intensity, or the equivalent inverse, environmental productivity. In macro-level studies, such as of decoupling of economic growth and environmental quality, environmental intensity is customary, defining eco-efficiency, for example, as environmental impact per unit of national income.

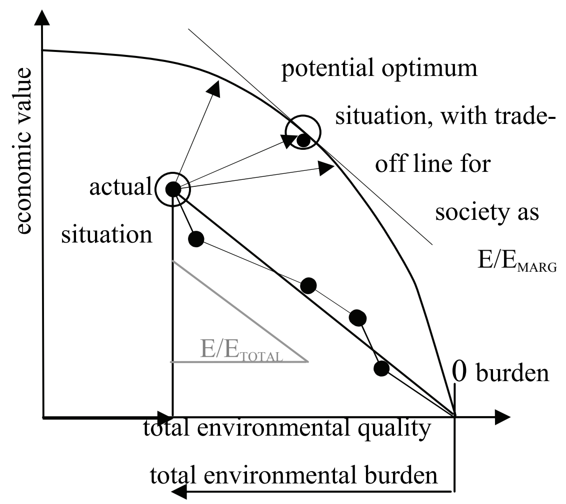

Figure 1.2 Eco-efficiency in society: Actual technologies, E/E_{TOTAL}, and production-possibility envelope with trade-off line E/E_{MARG} for society. Black dots denote specific technology domains

The marginal eco-efficiency score, based on pairwise eco-efficiency scores for each (black dot) technology domain relative to next possible options, has not been indicated for each technology domain in this macro-level figure. It could be depicted as a small, also concave curve within the envelope, bordering on the societal envelope. A rigorous mathematical treatment of this now graphically treated subject is still lacking. Without an explicit goal for the relevant trade-offs, we can be sure that this optimality score will be different per technology domain in practice. As a consequence, the actual situation facing society will not lie at the envelope curve of potentially optimal situations, where each point assumes a systematic choice based on the same trade-off for all choices in all technology domains. By indicating the distance from the actual situation to a point on the envelope, the "avoidable" sub-optimality is indicated, always relative to a normative choice on the economy environment trade-off. As discussed above, contrary to common intuition, both technologies with a higher value for the environment in their trade-off and those with a lower value contribute to the sub optimality. Each level of normative trade-off defines a point at the envelope, which then links to choices at the micro level with the same trade-off for all technologies in society. Clearly, our actual situation is not at a potential optimum point on the envelope. Making decisions in the right direction thus is not a straightforward affair. Should we focus on slow but fundamental improvements or is a catch-as-catch-can strategy the better option? Thus in real life more aspects must be taken into consideration than those of eco-efficiency itself. Should we accept that shifting investments between sectors is not possible? In a second-best world it may be wise to accept different trade-offs in different technology domains or sectors, for the time being, and actively search for less sub-optimal solution in the longer term.

Dynamic eco-efficiency

In reality, the technologies set as constituting the efficiency boundary assumed above does not exist or, more precisely, it is not well defined. We cannot shift between technologies at will, because such shifts involve adjustments in society, in the volume and nature of the capital goods industry, in terms of transport infrastructure, adaptations in regulations (not only environmental ones), and so forth. Also, at any point in time, in each technology domain, new technologies are emerging that lead to different sets of optimal technologies and hence to changing marginal eco-efficiency for the technologies considered. In reality, all technologies are path dependent, see for an early advocate of this non-classical approach Schumpeter (1943). All optimal technologies will become suboptimal in the course of technological progress. Implementation of new optimal technologies not only requires time but, even if possible, should not be done too fast. Installing any new technology directly would imply a continuous destruction of installed capacity, even if the destruction is creative also creating environmental costs. So adding real life dynamics would make the analysis much more meaningful, and much more complex. In shifting to full causal analysis—as is the essence of dynamic modeling—the easy aggregation by addition of technology domains has to be replaced by a causal model, indicating effects of choices and actions. Ideally, such an analysis indicates how the future would be different as a consequence of the choice made. Because this involves predicting the future twice when analyzing just two alternatives, this is a most demanding approach. Requiring real dynamic modeling for decision support would make eco-efficiency analysis, and any optimality analysis at the level of technologies, practically impossible. When eco-efficiency analysis is applied to practical decision making, the limitations of non dynamic analysis should of course be considered, at least in a further qualitative additional analysis. For now, more modest aims may be set for the analysis, starting with the simpler comparative static analysis depicted in Figure 1.3. This may be a starting point for deepening the analysis: how to deal with sustainability, including social aspects; how to consistently reckon with spatial and temporal aspects; how to relate to practical decisions in an appropriate way; and not just having solutions but making them consistent and transparent (Brattebø 2005). This simplified addition of dynamically relevant aspects is manageable in practice. Such simplifications are the more important because eco-efficiency modeling should be broadly applicable, including applications to decisions by consumers and by small and medium sized enterprises (SMEs) (Suh et al. 2005). Acknowledging the limitations of comparative static analysis, some insights may still be gained. First, the level of the trade-off, however disputed it may be normatively and politically, can be seen as an actual characteristic of society as exhibited in choices on technologies and policies. Different choices on marginal eco-efficiency in different domains clearly are a sign of sub optimality, assuming they do not result from deep dynamic insights. In developing new technologies, such indicative trade-off relations (Oka et al. in this book and 2005; Kuosmanen 2005) may roughly guide choices, leading to the development of a relevant domain of new technologies with substantially higher eco-efficiency.

Also, one may assume that with rising incomes in the course of time, the normative trade-off will shift toward more emphasis on environmental quality. Poor people cannot afford high costs for environmental improvement. This reasonable but not proven assumption may also guide choices in technology development in the right direction, that is, toward a range of feasible future trade-offs between economy and environment. In each domain, technology development will have to take place, leading to an envelope

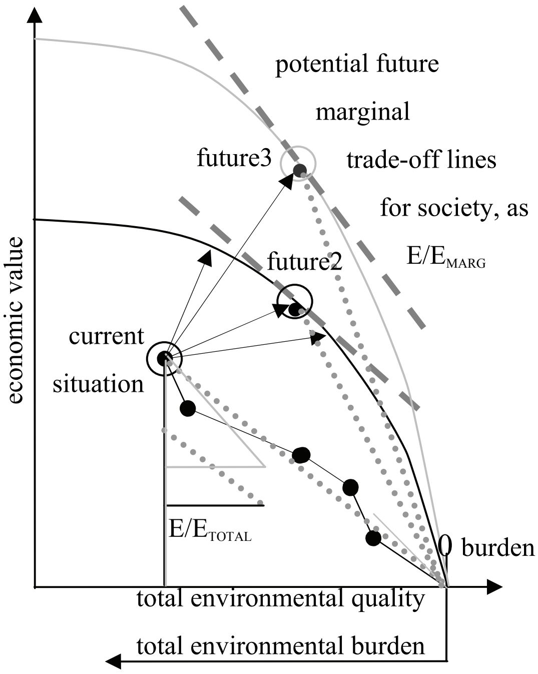

Figure 1.3 Dynamic eco-efficiency in society: shifting trade-off lines

of non dominated alternatives with a steeper curve from the zero burden origin. For society as a whole, this means that the environmental intensity curve will move upward, with the zero burden point remaining fixed. What can we learn from this theoretical dynamic exercise? At first sight, results are not comforting. All actual technologies improve as we grow, leading to the gray lines (with dots) in Figure 1.3 all becoming steeper because new technologies have been implemented. Damage per money unit of consumption decreases, but total damage remains constant. We may all become more affluent, but the environment will not improve. Only if we assume that actual trade-offs will shift, with more emphasis on the environment, may we move to a point where environmental burdens may decrease absolutely. If actual technologies lag behind optimal ones in the same proportion as they do now, this reasoning also holds for the suboptimal state we are in and will be in. Our efforts, already substantial, to remain constant in environmental burdens will have to go well beyond this for actual environmental quality improvement while we grow, or the warning of one of the first environmental economists will come true: “as ye grow so shall ye weep” (Mishan 1969, cover).

To avoid environmental regret on economic growth, two steps are essential both involving eco-efficiency analysis for their practical application. The first is to help move society in the direction of optimality, avoiding both too environmentally costly value creation and too high cost for environmental improvement. This is moving from current situation 1 to the more optimal situation 2 in Figure 1.3. The next step is to help guide economic growth. If economic growth takes place with the eco-efficiency of activities remaining the same, the environment will deteriorate. Even very weak sustainability requires eco-efficiency to move into a more environmentally benign direction, that is the steeper striped line in Figure 1.3.

1.7 Economic score

In the process of arriving at eco-efficiency ratios, the market part is to be quantified in one term, as cost or value, and the environmental impacts are to be aggregated into one score as well. Value and cost aggregation are well established subjects in two main domains, cost-benefit analysis (CBA) and life-cycle costing (LCC), both developed in the middle of the 20th century. Cost-benefit analysis has a broad societal point of view, disregarding transfer payments and correcting market values for market imperfections (for classics on this topic, see Mishan 1971, and Dasgupta and Pearce 1972). Like LCC, it takes a full systems point of view, covering “the life cycle.” Life-cycle costing, as developed for public procurement by the Rand Corporation in the United States, see for example the work of Fisher (1971), and by management accountants for application in firms, see for example the work of Dhillon (1989) both take a budget point of view, including transfer payments such as taxes and subsidies, and accepting the actual functioning of markets, including capital markets. Though for each approach different aggregates are possible, for example, as related to value-added or cost concepts, the underlying reasoning is well established and will not be much discussed in this volume. Both CBA and budget related LCC can express cost or value as a discounted present value. In the realm of LCA, discussions on how to align cost accounting to steady state LCA modeling, directly related to the eco-efficiency subject, may give rise to steady state cost or value as a third approach to LCC (see work by Rebitzer and Seuring 2003 on the LCA related SETAC Working Group on LCC and the survey by Huppes and colleagues 2004). Some conventions on specifying cost and value might come in handy, though, at least in specifying which approach is followed, how empirical effects are modeled, and which aggregation method is applied. For example, when eco-efficiency is analyzed from a broad societal perspective, as in analyzing climate-change policy measures, the logic would indicate a CBA type of cost and value analysis, such as the Intergovernmental Panel on Climate Change (IPCC) does in its publications (IPCC 2001). In CBA, though, economists tend to express market value and external effects as referring to the same value concept. This final integration step of external effects with market related magnitudes may better be postponed and, if done, be made as a recognizable last step, for several reasons. These reasons relate to, for example, the uncertain nature of environmental effects; the impossibility of specifying all effects in terms amenable to subjective evaluation by consumers; the lack of agreement on discounting when long time horizons are involved; the Brundtland principles of intragenerational and intergenerational justice and equity; and the divergence in stringency of actual environmental policies. So, in CBA for eco-efficiency analysis, the environmental external effects are kept distinguishable from market-related effects, avoiding at least some of these issues of contention.

In budget LCC and LCA-related LCC, cost and value refer to market related items only. For a given cost and value concept, numerous empirical issues must be resolved, especially if long time horizons are involved. In their comparative study on eco-efficiency trends, Dahlström and Ekins (2005) encounter the problem of changing market values of steel and aluminum, directly influencing the eco-efficiency scores. Historical studies may solve such issues by giving time series of prices as well. For future oriented studies for decision support, historical values are proxies for expected future prices. Especially for abiotic resources, which have shown substantial long term price decreases and volatility, expected prices may be highly disputed, and hence the eco-efficiency of decisions involving such resources as well. Uncertainties concerning the future cannot be avoided, but may be made visible to some extent by scenario development on main uncertainties. These then are reflected in ranges of eco-effiency scores, as a certain softness in results.

1.8 Environmental score

Environmental effects are those resulting from the choice at hand. Economic activities jointly produce environmental effects, for fundamental reasons, both in terms of resource extraction required for production, the environmental inputs, and in terms of losses from production, consumption, and waste management, as outputs to the environment. These relate to the first and second law of thermodynamics (see for example Baumgärtner et al. 2001 for a survey). Ultimately, there is no free lunch in environmental terms. But the environmental effects of all our lunches are far greater than thermodynamically determined minima, as calculated in terms of energy and exergy analysis (Baumgärtner and de Swaan Arons, 2003). Such analysis does not link in any direct way to biodiversity effects of economic activities. Clearing tropical rain forests is not a matter of thermodynamics but of socioeconomic and political dynamics. Though thermodynamics unavoidably rules, the choices we have go far beyond these physical constraints, and our environmental concerns, such as those in terms of human health and ecosystem health, cannot be reduced to thermodynamics analysis alone. So a main subject of diverging opinion in eco-efficiency analysis, not yet based on firm analytics, is how to specify and aggregate environmental effects. The intention is to cover all relevant environmental information, as the empirical part, and aggregate these empirical effects in a way that leads to a broadly acceptable single-score result, either focusing at efficiency only, as in Maximum Abatement Cost (MAC) method, or at least partly based on value judgments or preferences. With the relevant variables defined and agreed upon, the empirical part of effect (or: impact) analysis again is fraught with traditional problems in decision theory, with subjects such as before-and-after, with-and-without, indirect effects of varying complexity, and conditionality on compensating measures. Again, these subjects deserve attention and at least a specification of actual choices made in these respects. Which environmental effects are to be specified of course remains open to discussion. The United Nations propagates one specific method for impact assessment in the context of eco-efficiency reporting (UN 2003). In the realm of LCA, a survey of methods for environmental impact a nalysis is provided by Guinée and colleagues (2002) and Udo de Haes and colleagues (2002). These methods often originate in the public domain as efforts to standardize environmental analysis as part of the policy process such as, for example, in Japan (Itsubo and Inaba 2003), in the United States with the software Building for Environmental and Economic Sustainability (BEES 3.0 2004), and in the Netherlands (Guinée and colleagues 2002). Steps toward international standardization are ongoing, such as in the United Nations Environment Program—Society for Environmental Toxicology and Chemistry (UNEP-SETAC 2005) Life-Cycle Initiative. One point of basic agreement is on the distinction between *environmental interventions*, such as emissions, extractions, and land use; their *midpoint impacts* through main environmental mechanisms such as global warming, acidification, and toxicity; and the *endpoint impacts* of ultimately relevant items as related to human health (e.g., as morbidity and mortality), to environmental quality as an independent value and as the life support system (e.g., as biodiversity), and to human affluence (e.g., as reflected in production functions, landscape, and cultural heritage). Again the broad discussions going on in this field should be acknowledged when specific choices are made, but we will not go into them here. The focus here is on how environmental effects, when specified somehow, may be aggregated in a more or less generally accepted way. This acceptance is based on reference to what others in society have as views, values, or preferences. Two basic dimensions may help survey the field and clarify actual approaches. One is whose views and preferences are represented; the other is how they are expressed (see Figure 1.4). Whose views and preferences is it that have a general acceptance? In one approach it is all citizens in society, which is the economists' approach, or the direct democracy approach. Somehow individual preferences on environmental effects are aggregated into a social welfare judgment; see Arrow (1970) and Sen (1970) as main contributors to the analysis of this field.

In another, less formalized approach, the aggregation is through the political process, with public policy outcomes as the basis for the aggregated view. For both approaches, a fundamental problem is how to know the private and public preferences, either with stated views as a basis or with preferences derived from actual choices. In economics, broadly applied methods are interviews and panel procedures to measure the

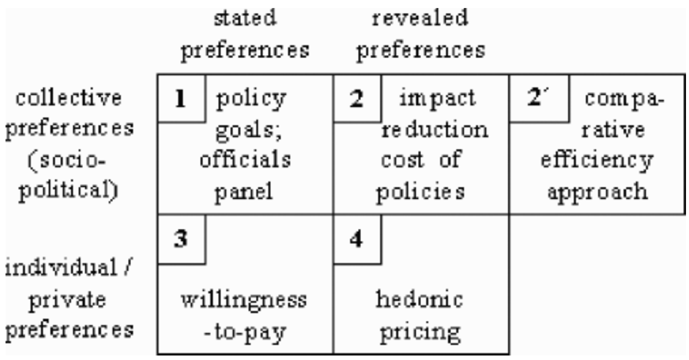

Figure 1.4 Five main types of aggregation for eco-efficiency analysis

willingness-to-pay for avoiding environmental effects (or to be paid for accepting them). The other option is to derive the preferences from actual choices, such as hedonic pricing, as for example inferred from lower housing prices for similar houses in more contaminated areas. Collective preferences similarly can be derived from public statements, as in policy goals in policy documents, or through interviews and panels with public officials. Or they may be derived from actually implemented policies, reflected in the cost deemed acceptable for their implementation, as revealed collective preference. Combining the two dimensions, four base approaches result, which can be expressed as weights on environmental impacts or the emissions and other interventions creating them. We will treat them in turn. Of course, it is free to anybody, or to groups of stakeholders in some decision procedure, to create their own weights, presenting their own preferences, or their views on future societal preferences. Such weights do not have the generality and authority striven for in the approaches now discussed in more detail. Special mention is made for an approach related to the revealed preference approach, but avoiding the welfare theoretical interpretation. It focuses on the actual cost of combined emissions reduction stating how efficiency in environmental improvement can be created, without knowing public or private preferences. This comparative efficiency approach is empirically filled in in this book in the paper by Oka and colleagues as the Maximum Abatement Cost (MAC) method.

Stated collective preference

Stated preferences may be derived from stated policy goals and from direct weight setting, as in panel procedures by public officials. In setting policy goals, such as reduction percentages or quality levels to be attained in a certain year, the preferences may be seen as a distance to target. Such distances, though, may already reflect assumed cost, because one would not set goals higher than implies a reasonable cost for reaching them. So, by estimating the expected cost for attaining the goal, a measure of the relative importance of the goal can be derived, in monetary units. An example with practical data on the Netherlands is provided by Davidson and colleagues (2005). Disadvantages of this approach relate to the somewhat ambivalent nature of policy goals, in that stated intention and effective later realization may not match, as seems to be the case in many countries regarding implementation of the Kyoto Protocol obligations. Also, using hypothetical costs of hypothetical technical options to reach the goals may grossly overestimate the more reasonable but vaguely expected "real" cost. Panels with public officials are another option for deriving stated preferences. Only a few examples exist, one from the United States in environmental analysis of building in the BEES software (BEES 3.0 2004), without a clear background of reasoning toward the weighting set being used (see Lippiat and Boyles 2001), and one from the Netherlands in an environmental covenant with the oil and gas industry (Huppes et al. 1997, with an update of the panel results in 2002; see Huppes et al. 2006 forthcoming). The advantage of this procedure is that the weights given can be directly related to specialized knowledge, such as knowledge of impact assessment models and detailed knowledge of the problem mechanisms involved. Application of these weighting sets is specific to a quantified problem description at a normalized level, for the United States, for the Netherlands, as in the case examples, or for other countries, or for the world. The broader application of such weighting sets should be based on more explicit public support for them, which now is lacking.

Revealed collective preference

Using the actual costs of emission reduction or environmental quality improvement avoids the vagueness of intentions and hypothetical technologies.

Especially if cases can be found stating the expected cost of actually implemented environmental measures, good insight into actually used trade-offs can be gained. But things are never so simple. In actually implemented technical measures for emission reduction, the costs are hardly ever assessed for a single emission or a single environmental problem. Reducing sulfur oxides (SO_x) emissions from electricity production by 1 kilogram typically requires 12 kg of carbon dioxide (CO_2) emissions, and has a further influence on virtually all other emissions and resource use in the world. Also, cost may be highly location dependent, as in exceptionally densely populated areas, where general ambient quality requirements are not met. Such incidental high costs cannot be seen as representing overall collective preferences. Wisely selected cases and sophisticated estimation procedures may reduce these problems to reasonable proportions. However, both stated and revealed collective preferences will now lead to diverging results, with consequences for the eco-efficiency analysis in these cases (see Nieuwlaar et al. 2005). Adding individual preferences or values based weighting sets does not solve this problem, to the contrary.

Comparative efficiency

In applying aggregation methods, one might wish to reduce the assumptions being made to a minimum. The most robust system available then is a variant of the revealed collective preference method. Its application may even avoid the interpretation as collective preference, by only stating the relative efficiency of options, relative to a base case, as in the maximum abatement cost method (see this book and Oka et al 2005). This may be seen as a special and practical case of the more general efficiency frontier approach (Kuosmanen and Kortelainen 2005). In applying the resulting weights to cases, one may see if the environmental improvement accomplished at additional cost (or lower value creation) might have been created for a lower price elsewhere. This does not entail any assumption on rational public preferences, just a reference to costs of emission reduction at other places. If enough data are available, cases with multiple emissions can also be covered in this way. This subject is also contentious, because surveys of cost per human life saved (for example as Disability Adjusted Life Years, DALYs) by different measures show widely diverging ranges;

see the survey by the U.K. Department for Environment, Food and Rural Affairs (DEFRA 2004).

All difficulties in the modeling of both costs and environmental effects are present in the cases covered in such survey studies, as Finkel (2005) and Ackerman (2005) nicely show in their reviews of Sunstein's Risk and Reason (Sunstein 2002) and Lomborg's Global Crises, Global Solutions (Lomborg 2004). A lively and often partisan discussion has taken place on the costs and benefits of measures, with as an extreme a much criticized survey study by Tengs and colleagues (1995), which has spurred volumes of discussion. In that study, actually implemented life saving measures ranged from negative and zero cost per life year saved up to $20 billion, with cost in many domains lying above one million dollars per life year saved, and an overall median of around $2000. By focusing on the actual current cost of emission reduction instead of the evaluation of environment and health impacts, some of these uncertainties may be reduced (Oka et al. in this book).

Stated individual preferences

The third approach, based on willingness to pay, is most widely used by economists and most widely despised by no economists. Its strength is that it fits in well to the general approach to economics based welfare analysis, in the dominant Pareto tradition. Its strength is in areas where a comparison with private decisions can easily be made, as in risk of acute toxicity, which individuals may compare to their own occupational risks and their risks taken, for example, in car transport and sports activities. When a clear link to morbidity and mortality is lacking, the link to environmental interventions may not as easily be established by an individual in monetary terms, or even in terms of preference ordering. This is the case, for example, with climate instability, where small-chance high-impact health effects are involved, on possibly long time scales. For broad surveys on this subject, see publications by Portney and Weyant (1999) and especially Kopp and Portney (1999). Also, in cases where non-health related risks are present, as with end-effects on ecosystems and biodiversity, the willingness-to-pay method breaks down in practice. The literature on limitations of the willingness-to-pay approach is vast. On the supportive side of the willingness-to-pay approach, a good survey of operational results of primary and secondary studies is provided by DEFRA (2004), including hedonic pricing and mixed methods.

Revealed individual preferences

Hedonic pricing, the fourth approach, looks at actual choices, its strength as compared to willingness-to-pay statements, which may reflect socially acceptable answers. The main problem is its limitations in application. In comparing different situations all other relevant variables should be kept constant. This hardly ever is the case with other environmental quality aspects, nor with variables other than environmental ones. For example, jobs or housing locations will always differ in many environmental respects, and also in non environmental ones. For environmental aspects not directly related to private quality of life, the hedonic pricing method cannot be applied. This includes future problems, for example, as related to climate change.

1.9 Combined eco-efficiency score

With the economic score and the environmental score ready for specifying the eco-efficiency of case options, there is one final choice to be made, on scaling. In CBA, the data have a meaning in money value. In all approaches not in monetary terms, or not recognizing monetary results as "real money," any linear rescaling of results may take place that does not in any way alter their meaning. Most case applications have such a scaling step, named normalization, both in decision theory and in LCA impact assessment. Two schools in this area respectively go for case-specific internal normalization and weighting, as is usual in decision theory, and for a "supra-case-level" external normalization, as propagated in LCA (Heijungs et al. 1992; Norris 2001). Because weighting is relative to normalization, the weighting factors are to be adjusted each time the normalization reference is adopted. The internal normalization is relative to the current situation, as done by Suh and colleagues (2005), or to the average score of the options compared, as done by Rüdenauer and colleagues (2005). The external normalization is relative to country level with the United States

(BEES 2004) and Dutch example (Huppes et al. 1997) mentioned previously, or to a global reference (Oers et al 2001 and Huijbregts et al. 2001). It seems that internal normalization and case specific weighting are not easily aligned, leading to a certain vagueness in case results. Also, some internal normalization methods may lead to dependence on irrelevant alternatives, where adding an alternative not chosen leads to a different preference ordering of relevant alternatives; see work by Arrow (1970) and Sen (1970). This is the case if a historical alternative is taken as the basis for normalization, as in eco-efficiency analysis of win-win situations. One further problem of case-specific normalization is that seemingly similar eco-efficiency scores cannot be compared between cases, and in some cases are not even comparable if new relevant alternatives are added, as when the reference is an average of the alternatives studied. A conclusion here is that if external normalization is available, it has clear advantages in terms of comparability of eco-efficiency scores between cases.

Further issues in implementation

The analytic framework is to be used in practice, filling it in with data on alternatives. In many decision situations, however, the required technology specifications are not available. Most policy instruments give only indirect guidance on development of technologies and products; in a design stage, specifications for eco-efficiency analysis are lacking; and major investment decisions usually involve larger numbers of technologies, which at least partly require further development before detailed eco-efficiency analysis may become available. In such situations, proxy variables may be used, related to aspects determining the ultimate eco-efficiency, and procedures can be developed for guiding actions toward eco-efficiency, as specified, for example, by Möller and Schaltegger (2005). This often will involve the knowledge and wisdom of experts. It also becomes of paramount importance to monitor past developments of eco-efficiency and its constituent parts, as therein lies the growth and validation of such expert wisdom. This monitoring first involves the performance of larger units such as firms, sectors, and regions. As in eco-design, though, replaying decisions with detailed hindsight would also constitute extremely useful exercises.

1.10 Summary and conclusions

Why eco-efficiency?

To meet the challenge of combining increased affluence with corresponding environmental quality, micro-level choices on the environment economy trade-off have to be aligned to macro level requirements. Practical measures of eco-efficiency are required, and mainly lacking.

What subjects for eco-efficiency?

Three basic situations may be discerned where eco-efficiency for decision making can be applied, each with totally different outcomes. Marginal eco-efficiency, as trade-off between potentially optimal alternatives, is most basic for decision making and can be applied at both the micro and macro level, whereas incremental eco-efficiency at micro level can be translated into environmental effectiveness at macro level. The third, use of the win-win type of eco-efficiency, seems not useful and even confusing.

Economic score

For the economic part of the eco-efficiency ratio, there are three basic approaches available, all based on life-cycle costing: market cost related values, as in management accounting and budget cost analysis; cost-benefit analysis, for the market related cost and benefits; and a steady state type of cost, conceptually best linked to steady state models for environmental analysis such as LCA. Establishing the economic score raises no fundamental problems, but several practical ones, for example, as related to discount rates and to mechanisms to take into account in the analysis.

Environmental score

For the environmental score, there is lessconsensus on what constitute relevant environmental impacts and what are adequate models for their empirical analysis, and on how different types of environmental effects may be combined into a single score. For the modeling of effects, a divergence arises with regard to relatively well established midpoint empirical modeling, linking emissions and other environmental interventions to environmental effects such as climate change and eutrophication, and more speculative endpoint models, linking environmental interventions to health effects, effects on ecosystems, and effects on production functions.

Discounting problems, as present in economic analysis, are even more prominent in environmental analysis due to the long time horizons of many environmental effects. Discounting also is difficult to reconcile with major sustainability considerations on intergenerational justice. Even if modeling choices are accepted, there are four or five fundamentally different options for combining effects as modeled into a single score. Keeping modeling and aggregation scores clear and explicit seems a minimum requirement, often not yet met.

Combined score
It is very common to transform the economic or the environmental score into a case-specific normalized score, in line with customary approaches in multi-criteria or multi-attribute decision theory. This practice deletes the information necessary for optimality analysis, as is required in comparing attractiveness of investments in different technology domains and in linking micro-level decisions to macro-level effects.

Applications
Similarly to the discussions on ecodesign and LCA, we may distinguish between actual decision support, often difficult because of lack of data, and the proxies and procedures used to guide decisions toward the desired eco-efficiency. Quantified eco-efficiency scores will be possible only at a certain nearly final stage of design. Historical studies, both on decision situations and on performance of larger units such as firms, sectors, and countries, would be very useful to build up expert knowledge on eco-efficiency of as yet vaguely defined situations, as is the case with most environmental policies and early stages of larger investment plans. One easy step toward better comparability of studies in different domains of application is not to rescale the environmental and economic scores relative to a case-specific option.

Prospects

A final environmental effect model will never exist, nor a fully agreed on method of aggregation of different environmental effects. Nor will full agreement be reached on details of establishing the economic score. Even so, disagreement is not so fundamental that scores could not be established with a reasonable level of acceptance, especially if it is shown how results depend on assumptions. Such transparency is lacking due to a lack of an explicit framework for eco-efficiency analysis. Agreement on such a framework, as proposed here, and consensus formation on main approaches for quantification is a clear task ahead, essential for realizing a better environment. One essential area of application is in the design of new technologies and products, as it is in this domain of *eco-innovation* that main environmental improvements will have to be realized.

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