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Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis[1]

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Summary

This paper looks at the compatibility between technological improvements at the micro-level and sustainability at the macro-level. The two main approaches to prevent environmental degradation are technological improvement and economic degrowth. How do we establish the sustainability of technological options? LCA-type analysis of the technology system, combined with economic cost analysis, offers a first integrated eco-efficiency score. However, such a technology analysis focuses on micro-level technology relations only, is usually too optimistic and ignores other constraints implied in a choice.

Fitting more comprehensive knowledge into the sustainability evaluation of options requires a unifying systematic framework, which is worked out in the present paper as a ten-step procedure. The integrative framework for empirical analysis is ultimately a comparative-static systems analysis at macro-level, not in a deterministic dynamic mode, which is impossible, but as a knowledge-fed scenario analysis. The analysis shows the change in society's overall eco-efficiency, combining total value creation with total environmental impacts.

Possible domains of application include not only technology choices like those in eco-innovation, including changed consumption styles and volumes, but also changes in policies regarding technologies and markets, whether direct policy shifts or indirect changes through institutional adaptations. Ultimately, such a framework also allows culturally framed questions about the type of society we would like to live in, to be analysed in terms of their economic and environmental consequences.

Key words
Technology assessment, Scale effects, LCA, Integrated assessment, Scenarios

Technologies and volumes

Responsible citizens, firms and governments would like to align their actions with the requirements of sustainable development. This is true for issues ranging from the choice of fuel to drive the car to the designing of environmental legislation and economic institutions, that is, the whole range covered in this special issue. But what is this sustainability to align with, and how can we know whether we are on the right track to alignment? Although the Brundtland principles of sustainability offer some guidance for arguing about the values involved, they do not provide any definite answers. The principles relate to distribution of welfare within countries, between countries and between generations. They have been transformed into requirements relating to income and income distribution, to justice requirements beyond distribution, linked to human rights, and to requirements regarding environmental quality and resource availability for future generations.

There are still substantial disagreements, however. For example, inequality can be viewed in different ways. Is increasing inequality allowed if it helps the poorest, as Rawls

[1] The International Eco-Efficiency Conferences from which this paper results have the *EBARA company* as their main sponsor. The paper also owes to work in two EU-FP6 projects, ECODRIVE, a completed project (see Huppes et al 2008), and the ongoing CALCAS project, see www.calcasproject.net.

(1972) defended? Is depletion of resources allowable if compensated for by increasing capital formation and productive knowledge development, as most main stream economists would agree? The normative requirements, especially if stated in absolute terms, have to be viewed against the empirical baselines of societal development, as variants of business-as-usual. Economically, the line leads to global industrialisation, with global incomes rising to levels similar to those in countries that are already industrialised; with legal and other institutions geared to economic growth; with science and education becoming core activities for development; and with policies supporting economic development and removing obstacles to it. Should such baselines be accepted as given, with environmental and social problems to be solved along the way? This would impose high requirements on technology development, technology in the broadest sense including the way consumers use products.

How are these requirements then to be defined; how do we know whether a technology is *fit for sustainability*? Is it possible to answer this question about technology as such, or only in relation to the broader characteristics of society, in terms of volumes of other technologies and of national income? Simple identities can show the way. The IPAT equation states that environmental impact equals population times affluence times technology. Technology is not a unit of activity as such, but is defined as *environmental impact per unit of final product*. (See Chertow (2001) for a more detailed treatment of the subject.) Environmental impact per unit of product is the main definition of eco-efficiency, raising subtle but important questions on how to define environmental impact and how to link this to a product. Technologists define products in functional terms, as is also done in LCA, while a business orientation leads to 'value created' as the numeraire, as explained in publications by the World Business Council on Sustainable Development (WBCSD 2000, 2001; DeSimone & Popoff. 2000, going back to Schaltegger & Sturm 1990). National income is the other part of the equation, corresponding to population times affluence, with affluence being defined as income per head of the population. It is not the product as such which has the impact, but the *product system*, consisting of the activities related to the product.

If economic growth is not assumed to be preponderant and unavoidable, how can realistic and normatively relevant degrowth or slow-growth scenarios be designed (see: www.degrowth.net/), which can function as a background for technology evaluation? Technologies will play a dominant role in economic development as well as in environmental quality, resource requirements and resource depletion; this is also true in degrowth scenarios. This paper sets up a framework for the sustainability analysis of technologies, allowing for the systematic and transparent use of relevant information. The resulting answers will always be soft and hence disputable, given different views on sustainability values and different views on what is realistically possible in shaping our future. Resolving the current stalemate in analysis seems essential, at least narrowing down the domain of relevant discussion. Overarching strategies like *biobased society*, *cradle-to-cradle* approach or *dematerialisation* may give some idea of the directions that might be interesting. They do not, however, provide answers on what exactly to do. The unpredicted disasters resulting from large-scale introduction of energy from biomass offer an example of the gaps in our 'normal' analysis. It will be inevitable to analyse options in the concrete terms of their fittingness for sustainability. The question is how to do it. One main approach in the analysis is that establishing fittingness always involves a trade-off between economic elements of affluence, our industrial production and consumption of goods and services, and the quality of the environment, as an amenity in itself and as a source and basis for industrial society. Therefore, the concept of eco-efficiency plays a central role in the analysis, both at an empirical level, in terms of assessing the eco-efficiency of a technology, and normatively, in terms of assessing how high this eco-efficiency should be to be fit for sustainability, in the shorter or longer run. The key issue in this paper is how the analysis of technologies, as micro-level entities, can be linked to the macro-level performance of society, in terms of its macro-level eco-efficiency and its broader sustainability performance. The Ten Steps form the core of the paper, with the example of bioenergy illustrating the principles and relevance of their application.

Should we join the slow-drive movement?

One example may show that even options that seem obviously good might not be so good at closer inspection. Let us analyse one option that is widely available to help bring about a more sustainable society, the *slow-drive movement*. Several European governments have picked up this idea for carbon saving, the Dutch national eco-drive programme New Driving ('Het Nieuwe Rijden') being an example. As they state, measures to improve car driving behaviour offer the potential of considerable fuel savings and consequently reduced CO_2 emissions from traffic. Both the EU and UN/ECE, OECD and ECMT (European Conference of Ministers of Transport) have repeatedly concluded that such measures are potentially effective. In the US, a grass-roots movements is propagating the same idea, with bumper-sticker campaigns[2]. Let us assume the movement is successful and that all car drivers in the world join. By accelerating less, driving more slowly and braking more carefully, everybody saves 10% on gasoline, resulting in huge oil and carbon savings and also in reduced emissions of several substances. This would seem a clear case of a win-win situation, for which one does not even need an LCA or MIPS. But now doubts arise. First, an elaborate LCA would show that cars would have a longer life span, so older cars would become more dominant in the fleet, with technical progress trickling through more slowly. For the fleet as a whole, the advantage in the longer run would therefore be smaller as compared to the instantaneous choice of an individual driver now. The question to be answered has changed slightly in this step, allowing for a more encompassing analysis, with a different time horizon. Framing questions relevantly is an essential starting point for analysis and evaluation.

We can now expand the analysis further. What happens to the income saved by using less fuel and buying fewer cars? The general productivity and hence the incomes of the slow drivers remain roughly the same, so a huge amount of money is diverted to other consumption, as an income effect. The marginal propensity to consume in industrialised societies favours long-distance holidays and higher quality food. In terms of negative environmental effects, these outcompete car driving (see the outcomes of the EIPRO study for Europe in Tukker et al 2006), especially in countries with high excises on gasoline, like Europe, Japan and increasingly some US states. A further rebound mechanism would be that consumers compensate for the additional driving time by switching to modes of consumption that save time, which need not be very environmentally friendly.

Next, what would the oil and other energy producers do when car fuel demand is cut by ten percent? It is hardly likely that they would reduce production by the amount involved and keep prices stable relative to their autonomous development. Competition will mean that prices will drop, oil production will be reduced somewhat and other applications of oil will partially fill the gap created by the slow-drive movement. Air transport will be a clear winner, further reducing the environmental attractiveness. The lower fossil energy prices will have a negative effect on technology development towards low-carbon energy systems, as experience after the oil price peak of the 1980s has shown and as technology dynamics models show in general. Furthermore, there will be effects on income distribution, both between countries, with oil producing developing countries being hurt most, and within countries, with unclear direction. There will be numerous further effects, such as those on tax proceeds, resulting in

[2] See: greenslowmovingvehicle.squarespace.com/

changes in taxing rules and public spending, with sustainability consequences that are hard to predict. If we expand the analysis to other environmental effects, beyond those on climate, it becomes even more complicated, and again less clear-cut.

So far, the reference for comparison has been current society, rather than an alternative future state, as would be more relevant. A more fundamental question is therefore whether such a slow-drive car system would fit into a future sustainable world, where climate changing emissions are reduced by eighty percent by 2050? This will definitely not be done with current cars and the current level of car use. Is the slow-drive movement bad for our common future, as it is not in line with the substantial absolute decoupling which is required? If we replace the slow-drive option with ten percent fuel efficiency increase in all cars delivered by producers, with car prices remaining equal, the effects on economic and environmental performance will be exactly the same as those of slow driving, from a technological point of view, although this option will mean a slower introduction, as the fleet has to be replaced. Is this ten percent increase in fuel efficiency of cars sustainable or not? Careful selection of frameworks and mechanisms to be included can probably prove either outcome. Our gut feeling says: of course slow driving is good for sustainable development. But then, gut feelings should not be trusted so easily.

How then can we set up an adequate analysis, also covering cases which prima facie are less clear-cut, and cases involving more fundamental longer-term changes? There is no simple answer to this question, but a comprehensive approach is needed to answer them, disentangling and structuring the web of overlapping relations and disconnected domain knowledge. This approach comprises three basic steps. The first is the exact formulation of the questions to be asked, that is, how they are framed in terms of broadness, newness of options and time horizon. The second is to establish empirical relations and mechanisms involved in society and the environment, leading to effects specification. The third is the combined empirical and normative analysis, leading to an evaluation of the sustainability of the options considered. This is where eco-efficiency comes in, first giving the trade-off in terms of the effects on income and the environment as empirical eco-efficiency, and then the fittingness in an overall sustainability framework, as normative requirements on eco-efficiency. The normative position of ***strong sustainability*** can be directly translated into eco-efficiency requirements on technologies, given some assumptions on economic growth or some way of modelling economic growth in the analysis. Within the strong sustainability position, different views are possible about the emphasis regarding economic growth and environmental improvement, again leading to different requirements on the eco-efficiency of options. The position of ***weak sustainability*** requires more subtle reasoning towards trade-offs, for instance involving a more explicit social welfare function; see Neumayer (2005) and Dietz & Neumayer (2007). Once again, there are many specific options for evaluation.

Shaping our future through multi-level decisions

Eco-efficiency analysis primarily relates to technologies, and developing and implementing technologies involves a wide variety of decision types. These range from choices about products and technologies to policies on technologies, strategies for development of technologies, and ultimately the development of institutions to create and guide the dynamics of technology development and economic development in general. For the short term, specific policies may help create specific product-technology combinations. In the long run, however, it is institutions that determine longer term development, as historians from various backgrounds have stated (North 1981, 2005; Freeman & Louça 2001; Mokyr 2002), and as economists increasingly agree. Institutions create the incentive structure for economic actions. Direct government intervention in markets may well have a negative effects on technology and market development in the longer run, as Mokyr (2002) has shown for the delayed industrial revolution in France as compared to England.

The time frames involved may differ substantially. Eco-efficiency requirements for improving on current operations are less demanding than those for helping create a sustainable (or more sustainable) society by the year 2030, 2050 or 2100. At each date, there will be only one reality, but which one it should be (and will be) depends on views and decisions. A slight improvement in current eco-efficiency will surely create a disaster if achieved by 2050. The future is not fully determined, but not fully open either, so requirements have to be set daringly and realistically. All our choices influence the way our future will be shaped. Some choices are so predictable that they seem 'determined'. The predictability of actions, however, depends on institutions and cultural aspects, which themselves may be seen as malleable and are prime subjects in sustainability considerations, especially when trying to achieve demanding sustainability goals. Whatever freedom we have in shaping our future, there will be only one future which we will all share, though we may view it differently. We will have to create common knowledge, and have to relate this explicitly to overlapping norms and values, in a practical sense.

Differences in views on options may relate to the availability of options and to views on their attractiveness. There is not one sustainable future, but there are many views on what constitutes sustainability, as is already clear from the differing positions regarding weak and strong sustainability. Getting to the future requires some social and political agreement, if only to avoid mutually conflicting actions for sustainable development, which would make all of them less effective and more costly. We do not discuss this political aspect, though policies and institutions will be referred to at the end of the paper.

Economy and technosphere linking society and environment

The starting point of our study is a systems approach to the analysis of both society and the environment. Economic activities form the key link between society and its environment, with habitat management as a major additional link. On the societal side, economic activities forming the *economy* relate to culture, institutions and policies. In the physical layer of the economy, the *technosphere,* these economic activities relate to the natural system forming its environment. The systems analysis in current social sciences is a product of the 1940s and 1950s, linked to names like Talcott Parsons (1951) in a more equilibrium-based version, to Amitai Etzioni (1968) in a version involving the dynamics of social action, and later in the 1960s and 1970s to management sciences, as developed by students of theirs like Niklas Luhmann (1989; 1995) and Renate Mayntz (1984). In this approach, society is regarded as consisting of major elements or action domains, which have an internal structure and external relations with the other elements of society and with its surrounding environment. Various approaches and terminologies have been developed, which seem to converge into, or at least are covered by, four basic categories in the social system: Culture, Institutions, Economy and Polity.

Culture involves knowledge, beliefs and values, as well as education. Institutions structure society and create incentives, through organisations and legal rules on ownership and liability and financial reporting. In the polity, views and power are combined in binding decisions for society, regarding economic activities, institutions and culture, especially through education. The economy feeds society with goods and services, building on its technosphere base, and is guided by the three other systems of society. No similar goal-oriented structure is present for the natural system. The functions for society can be specified as being related to ecosystem functioning, especially the life support system and biotic resources and the non-living physical system from which abiotic resources come, including solar energy. However, as subsystems, they overlap, in that physical climate mechanisms, for example, are intertwined with ecosystem functioning, as are geological processes on a different time scale.

Technology forms the physical interface which allows a link between the culturally determined value created in the economy, as the economic part of eco-efficiency, and the impacts on the natural system, covered by the environmental part of eco-efficiency. Of course, the aggregation step towards the two main categories is not just empirical but also value-based, not only as regards the economy and society but also in the way the physical environment is specified and aggregated. As regards society, we focus on the economy, leaving broader social issues and values for later consideration.

Around here

Figure 1 Technosphere linking Environment and Economy

Time frames and reference situations

In analysing the sustainability potential of options, the time frames involved are decisive for the set-up of the analysis. What is a leapfrogging improvement now, creating an environmental improvement by a factor of 10 per unit of function, may be very insufficient in the long term of steady economic growth. This argument is all the more valid since not all technologies can make such jumps, whereas society as a whole should be on a path of absolute decoupling. Substantially improving the energy efficiency of gas stoves, for example, is hardly achievable. However, the long term may also create new conditions in which old and hard to improve technologies just become obsolete and irrelevant. If cheap solar energy becomes dominant in the long run, gas stoves will disappear anyway. Conversely, many electricity-based technologies that are currently unsustainable may well become sustainable without any technology improvement, as abundant solar energy becomes available. The open nature of the future is a matter of the choice of time frame. For next year, the role of fossil energy is fixed to the level of a few percent change at the most. For the next decade, some larger shifts are possible, up to maybe ten percent change. For the next century, we may have terminated the use of fossil energy altogether, if global institutions guide us that way. Predictions, at least reliable ones, are impossible over longer time scales, as the future is not determined. Many scenarios may look attractive but may not be feasible, in a down-to earth back-casting analysis. Solar energy with an energy payback time of three years can be introduced at a certain maximum speed only, as more speedy introduction would require non-solar energy to be substantially expanded first. Also, many current environmental technologies require rare metals like indium, which are in limited supply, at least on a time scale of decades. Almost all fundamentally new technologies require a longer time horizon before they can achieve a substantial market share (Huppes et al 2008, Hirooka 2006). Sometimes large-scale introduction never happens. The Stirling motor, which is superior in energy efficiency to gasoline and Diesel engines, has encountered various problems since its design and patented introduction in 1816. Even after one and half centuries of further development, only its reverse application in cryogenics has been successful.

After development, successful introduction on large-scale markets typically requires around three decades, as Hirooka convincingly claims for fundamentally new product-technology domains (see table 1). He distinguishes three consecutive trajectories for innovation: the technology trajectory, the development trajectory and the diffusion trajectory. The technology trajectory refers to the development of the fundamental science and related technologies. The development trajectory refers to the development of products/technologies that are based on this fundamental knowledge. The diffusion trajectory refers to market formation and diffusion in the markets of the products that have been developed. Hirooka shows that all three trajectories follow a non-linear, logistic path with major changes taking place in the steepest part. The distance in time between these central points in the three trajectories is typically around three decades for the development trajectory, an interval which has not shortened in recent decades, followed by one decade for market diffusion. Given a scientifically developed technology, the stage of mass diffusion thus typically comes after forty years. Even if we do not follow the Hirooka structure for analysis, the time frames will be more or less the same. There is no reason to assume that these trajectories will be shorter for eco-innovation. On the contrary, the direction and stability of incentives is less clear in this case, possibly leading to even slower effectuation. Specific new elements of existing product systems may arrive on the market faster, like the GMR magnetic hard disk readers. These were developed independently by Fert (France) and Grünberg (Germany) in 1988, winning them a Nobel prize in 2007. This technology became the basis for iPods (US) and other small disk-based apparatus, and for large-volume data storage as used in the expanding web services by Google (US) and Yahoo (US). This technical element in an already developed system took around 15 years from technology development to large-scale diffusion, which in the current context is always global.

The gist of this analysis is that when judging a technology in terms of its potential mature market functioning, the reference system, with its position in time, depends on its complexity and current development stage. Complex systems that are currently in the technology development stage, like new energy conversion systems, typically require another four decades before market maturity, if they ever become successful. Their sustainability analysis and evaluation therefore has to be framed for that future situation, with eco-efficiency improved by a factor of the order of at least 4. Changes in existing systems can achieve market maturity much faster but have a more limited impact. On the other hand, the sum total of small changes is more important than the big jumps, at least for economic development. This might well also be the case for sustainable development, if environmental incentives could be developed which become as strong as the current market-based incentives.

The dominant role of old technologies in economic growth has been extensively investigated (see Edgerton 2007). This factor also indicates how difficult it is to speed up economic and environmental change: technologies are intertwined and there can be no central coordination for their interrelated adaptations. Could central government action help, with governments making technology choices and implementing them? The general ecological trial-and-error mechanisms could well stop if active central coordination is introduced, easily leading to a slowing down, instead of speeding up, of general development towards sustainability. It is easier to put a man on the moon than to change the world towards sustainability.

Table 1 From technology development to product development and market diffusion
Source: Huppes et al 2008, adapted from Hirooka 2006.

	Trajectories				
	Technology	Development		Diffusion	
	T=0.5	T=0.5	Time lag (year)	T=0.5	Time lag (year)
Synthetic dyestuffs	1845	1880	35	1893	13
Biotechnologies	1960	1993	33	2004	11
Electronics	1960	1986	26	1994	8
Computers	1943	1977	34	1989	12
ISDN	1969	1992	23	2003	11
Multimedia	1974	2002	28	2013	11

Empirical and normative analysis

More specific decisions require the framework to be specified, ultimately covering at least the technologies and their volumes which determine both our affluence and the relation with our environment. Although there is not one model which can incorporate the dynamics of societal development, there is substantial knowledge in several domains, both in terms of specialised models and in terms of general background knowledge relevant to sustainability decision making. The subject may be framed in terms of transdisciplinary research; see Hirsch & Pohl (2007) for an open treatment of this subject. The potential procedural aspects of the analysis, in terms of stakeholder procedures, should be kept apart from the analytical structure. The procedural aspects are beyond the scope of this paper, though they are, for example, part of the EU-FP6 CALCAS project (see www.calcasproject.net). The main lines of reasoning are in figure 2, with elements specified in more detail in figure 3. The analytical distinction between empirical and normative analysis does not mean that these domains are independent. What we cannot analyse we cannot have values about, to adapt Wittgenstein's phrase, and what we do not have values about, directly or indirectly, does not require analysis.

Around here:
Figure 2 Sustainability evaluation through linked empirical and normative analysis

Ten basic steps in the sustainability analysis of options

How can we embed the eco-efficiency analysis of technologies in their relevant knowledge domains? The knowledge contained in many models is diverse, complex and dissimilar, if not in fact disparate, inconsistent and conflicting. For example, the climate models used by the IPCC are dynamic, and one part of them relates to climate forcing. The effect on climate forcing of an additional emission of some substance can be specified against a background scenario. This climate forcing effect can then be time-integrated over a specified period, usually twenty, fifty or a hundred years. This yields the global warming potentials, as $GWP_{[time]}$, for the substances involved, scaled per unit of mass relative to the climate forcing effect of CO_2 in the same time period. How can we use these GWPs in a consistent way? It cannot be done in a dynamic model, as that would require disaggregating the climate forcing outcomes of the model. Nor can it be done in a future scenario based on solar energy, because the scenario assumptions underlying GWPs would then be wrong; nor in a short-term action framework focusing on the prevention of disastrous short-term run-away effects such as might occur if large methane deposits are released, because the period covered in these GWPs is too long for such mechanisms; nor in long-term views on world development over centuries, because the time horizon in GWPs then is too short. Whatever option one chooses, full consistency with other models is hard to achieve, but leaving climate change out of the analysis is obviously even more wrong.

The diversity of options for analysis is large even if we focus only on this relatively simple, mainly physical type of climate forcing model, as one example of an environmental model. As the right-hand column of the specialised models in figure 3 shows, each of them offers a large number of options, each making a real contribution to our understanding (after removing overlapping and irrelevant ones). Combining all relevant possibilities in all modelling domains makes it very hard to achieve a sensible evaluation of options. Complexity will make reasoned choices quite impossible. Worse, by selectively picking particular mechanisms and modelling relations we can create any outcome we like, with interest groups choosing the analysis that works to their advantage, and consultants doing a seemingly nice scientific job for them. A toolbox, if extensive enough, will deliver any outcome one may wish. Somehow, we have to create an integration framework, on the one hand to reduce complexity and on the other to clarify the simplification choices which have been made in the integrative analysis. The framework must be used in such a way that its structure is able to incorporate knowledge from all domains relevant to sustainable development, including both natural and social sciences, using a more or less specified value system. The framework has to be such that human decision makers can handle it: combining different dynamics of different options in different empirical domains is beyond human handling capacity. In fact, evaluating more than five independent categories is beyond normal human capacity, with only exceptional people reaching seven. A stepwise reduction of information in a modular manner seems the only option, with consistency and relevance rules to allow for a rich analysis with more or less impartial outcomes.

Step 1 is to define precisely what the options are, in terms of technologies and technology families, and exactly what questions are to be answered. The 10% improvement in car efficiency achieved by slow driving is an option that can be introduced now and is definitely useful. A 10% increase in fuel efficiency of new cars coming on the market in 2012 will gradually penetrate into the fleet by 2025. By then, a 10% increase will be well below eco-efficiency standards required for absolute decoupling, due to the economic growth which will have doubled global national income, if crisis or wise policy does not halt us. How to adequately frame questions, as step 1 in the framework, is an art not yet well developed. The time frame involved is clearly a key issue, directly related to the choice of a relevant reference situation. The ultimate question will always be 'how will the world be different if we choose option x rather than option y'. This comparison is to be made not with the world as it is now but between the optional worlds of the future, as an explicit full comparison. Only in special cases might this analysis be reduced to a difference analysis. Of course, improving on the current world is the aim for all futures, and the question to be answered is how to do so best.

In ***Step 2***, the specific technology investigated is placed in its technological context, forming a technology system, in an LCA manner. All processes involved are quantified in terms of per unit environmental impact and cost or value creation, and linked together in the *technology system* for the technology investigated. This can be done in LCA, reducing the system to activities for the functional unit only, or more generally as a system with several useful outputs, including that of the functional unit. This option avoids the problems of allocation, but makes the comparison more difficult. Together, the economic and environmental scores define the micro-level eco-efficiency. This is where many studies stop. There are then two main options to proceed, viz. placing the technology directly into the macro-level context of step 9, by assumption, or going through all possibly relevant mechanisms and relations which can condition the functioning of the technology, and only then taking the step to the macro-level.

A wise person takes precautions and goes through the relevant knowledge domains. He would then start at ***Step 3***, the more comprehensive technical models involved, both in the new technology itself and in the processes forming the technology system. The knowledge in these models allows for views on how the technologies might adapt to different situations, which cannot be done in the linear LCA-type models with fixed input-output relations. Engineering models are widely used in research and industry, often with optimisation modules. The adaptability of processes is also an input in the supply functions of step 4.

The next point is the volumes in the markets involved, which are analysed in ***Step 4***, the last micro-level step. The analysis of markets not only concerns the product markets of the technology system itself, but also those in markets influenced by it. Combined supply and substitution are universal mechanisms. For instance, additional demand for corn-for-fuel will raise the price of corn (as maize) and of corn-growing land, which in turn will increase corn hectares and the volume of production of corn and stover, a fodder in pig and cow production. Prices of all other products competing for the land taken up by the corn will rise. Markets can be analysed one by one, which is the easiest option. The check on mutual consistency of several single market models can be done by integrating them into in partial model. However, if real elasticities of supply and demand are used, including cross elasticities, the complexity becomes very large even with limited numbers of markets covered. Covering the most relevant market provides insights into effects as such. The outcomes of the market analyses can be incorporated in the meso-macro analysis of Step 9, quantifying a number of sectors in more detail. Some consistency requirements, such as taking account of overall demand, supply of factor inputs, etc, will qualify the outcomes of the micro-analysis in this integration step. Market analysis is widely available for current markets. The relevant markets for longer-term decisions, however, are those of the future.

In ***Step 5***, the analysis moves to the physical flows involved, to view constraints and options. Most new environmental technologies, for example, use rare metals that are in limited supply, as in many types of solar cells. Although in the longer run, recycling can reduce primary production requirements, primary production has to deliver in the stage of building up capacity. Even relatively old technologies, like pipelines for large-scale carbon storage and sequestration, cannot be introduced within, say, a decade, since that would require, for example, an improbably high increase in nickel production within the next few years (Kleijn et al 2008). Where there is a substantial influence on specific materials flows, a dynamic materials flow analysis is required; see Elshkaki (2007) for a detailed analysis and survey. This analysis must usually be a global one, as most resources are global commodities, exceptions being certain abundant low-value materials, like granulates. Freeing materials for other purposes can also be a relevant part of the analysis, thus covering both materials constraints and options. Similar reasoning holds for energy analysis. More specific types of energy analysis, like exergy analysis, can be part of the technology modelling in Step 3.

The next domain of modelling, ***Step 6***, covers the more aggregate level of economic modelling of society as a whole. These models usually cover the economy using an aggregate input-output model, adding a limited number of behavioural mechanisms. These can focus on overall dynamics as related to trade flows, labour market developments and general technology development (eg Duchin 2005). Or they cover one sectoral domain, like energy, in some detail, like a partial equilibrium analysis, with the remaining parts of the economy made consistent using an input-output model. This is the usual set-up of CGE/AGE (Computable/Applied General Equilibrium) models. Examples are European energy models like PRIMES and GREEN-X, with specific applications, for example on energy & climate policy analysis in Portugal; see Simões et al (2008). Although these macro-level models can usually be set up as dynamic models, applications tend to be comparative-static, stating two or more potential states, and not the development path. Partial equilibrium models, as a series of linked market models, do not necessarily link to the overall economic framework, making them a set of related market models like those treated in Step 4. There are many such general equilibrium models. Their level of aggregation in the sector part is too high to sensibly link them to more comprehensive sets of environmental interventions and to develop hybrid models with detailed technologies, like those used in step 9. Their set-up is very similar, however, in that they can be presented as snapshots, as slices in time, with activities and their effects specified per year. Thus, linking is possible, eg as a constraint on the more detailed models.

Step 7 considers more comprehensive social science models. Though usually not highly quantified, they play an essential role in specifying the reference situation and prioritising the role of mechanisms. An example is the long-term modelling of bio-energy technologies. Cultural, institutional and political models might be treated as separate steps. Together, they may cover a number of mechanisms, like the structural developments in consumer demand, the further globalisation of markets and the development of new environmental policies. Such developments may be analysed empirically, or they may form the basis of specifying scenarios. To show how essential this step is, let us look at an example. Currently, high biomass prices are causing rain forests in South-East Asia and South America to be transformed into agricultural lands, whether uncontrolled, planned or somewhere in between the two. In the long run, this will hardly be the case, however, as developing countries will have become industrialised, with stronger governments and stronger environmental priorities, and with much less rain forest left by then. Generally speaking, the micro-level analysis of steps 3 and 4 has to be embedded in macro-level models. As in all steps in empirical analysis, the time frame of the question determines how modelling is to be set up, and how appropriate available models, usually representing past relations, are to answer the questions for a nearby or faraway future.

All relevant information of the preceding steps is to be reflected in the macro-level integration in ***Step 9***. The conceptual framework is that of hybrid input-output analysis with environmental extensions. This hybrid analysis can be set up as a data-solving approach for LCA, as a micro-level analysis, or as a macro-level analysis with detailed technology specification by disaggregation of specific sectors (see Suh and Nakamura 2008; Heijungs 2001).

This new type of modelling option has become available only recently, with the availability of detailed input-output tables with broadly covered environmental extensions. Two main databases currently exist, one for the US (see: CEDA3.0) and one for the EU, the EIPRO database (now: E3IOT, see reference). Japan has detailed IO tables but with limited environmental extensions only. The Japanese database has been used to analyse waste management (Nakamura et al 2007). The EIPRO database has, for example, been used for hybrid analysis of fuel cell buses for city transport (Cantono et al 2008). Fitting in specific technologies can hardly be a mechanical procedure. Even detailed IO models still aggregate technologies, making links to specific technologies in the hybrid analysis a somewhat cumbersome procedure. The knowledge base for this analysis is being improved, for example in the ongoing EU-FP7 project EXIOPOL (see reference). Other constraints may be soft as well. Overall, we know that the land surface of the earth is limited, so using more of it for one purpose necessarily detracts from other purposes, but intensity of use is a variable as well. Somewhat softer still, such restrictions also hold for labour supply, savings and investment levels, etc. The task involved here is to integrate knowledge from complex models into a simpler overall modelling framework, around a reference year. The technology specification of step 2 needs quantification in terms of market volumes, as made in step 4, but made consistent with macro-developments and with partial mechanisms in the other empirical steps.

The outcome of step 9 is the *Economic and Environmental Performance***,** stating the *Effects of Options*. These are snapshots that may cover parallel scenarios and a series of years. And they may not only include the environmental interventions, but also some integration further down the chains of environmental effect involved, like climate change. The analysis should also include an evaluation as to the status of results: to what extent they are based on assumption; to what extent on educated guesses; to what extent on corroborated models etc. As the outcomes relate to scenarios (the future cannot really be predicted), validity and reliability are of a different nature than with measurements or with simple predictive modelling, where uncertainty can be quantified in terms of accuracy and precision.

The relation to environmental models, as **step 8**, is slightly different, as the environmental effects will mostly be dependent variables, with so far limited physical feedback into technical and economic models. We therefore still can treat it after the integrative step 9, as a simplification. The dynamic specification may be relevant for specific questions, as when analysing the risk of runaway climate effects. The modelling set-up will generally be as follows. The activities of specific actors and sectors as specified in step 9 create environmental interventions, such as extractions of resources and emissions of substances. These are specified for a period, usually as one-year snapshots or as an equilibrium for a fictional year. The environmental effects resulting through further mechanisms will be more dispersed in time, and involve substantial non-linearities. This step in the analysis may best be implemented after the integrative model, for now a hybrid input-output model has been set up. The integration as in GWPs is convenient, as ultimately an overall judgement is to be made by decision makers facing a choice of options, but it is not always consistent with the question to be answered.

The final step, ***Step 10***, should result in reasoned answers as to the *Sustainability Evaluation of Options* investigated. With effects of options specified in terms of ***how the world will be different*** if a particular option is chosen (the with-and-without comparison, not the before-after comparison), the final question is how to judge the various resulting effects. While a wise man may know the right choice intuitively, the argumentation in societal discussions has to be stepwise and transparent, bringing together the mostly conditional empirical results and combining these with the normative part of the analysis. Some would advocate a social welfare function, or opt for a cost-benefit type of approach. There are no ideal solutions here, as applied social welfare functions are not available and cost-benefit analysis is based on normative assumptions not widely understood and accepted outside the domain of mainline economics. We will have to make do with the sustainability framework. Some steps are difficult, some reasonably clear. The most encompassing step involves the quantification of an overall economic and an overall environmental performance score. The economic score is in terms of affluence, using some variant of national income, and the deviation from this which is induced by choosing option x. Similarly, society relates to the environment through the sum total of its interventions, which is somehow to be integrated in a grand total, first by adding up similar empirical effects and next based on values, norms and preferences. The option x investigated may be quantified relative to base option y, for example the business as usual scenario for society. Having these outcomes we can see how specific choices can lead to eco-innovation. Economic improvement with environmental degradation and vise versa require a trade-off economy-environment as can be supported by weak sustainability considerations. With several options specified, a production possibility envelope can be constructed, with inferior options lying inside the envelope. Also with genuine eco-innovation, choices between several options on the envelope require a view on what constitutes a reasonable trade-off economy-environment, to be expressed as pairwise eco-efficiency score. Decoupling considerations would not take the future business-as-usual situation as a reference but the current situation. Absolute decoupling would require an improvement in eco-efficiency performance in time higher than economic growth.

Part of step 10 is formed by an interpretative analysis of the extent to which the outcomes are fit for well-informed decision making. This analysis of fitness links back to the way questions have been framed, how they have been answered, how different types of information have been incorporated, what were the weak spots in the models used, where more qualitative notions may be more important, how apt the comparative-static model is for the decision at hand, and how the normative analysis might be further specified in relation to norms and values. These reflections may lead to further questions and possibly to the formulation of a next round of analysis. The incorporation of background knowledge has a similar function, as we always know more than what has specifically been modelled.

Around here:
Figure 3 Ten basic steps in sustainability analysis of technology options.

Micro-level technologies linked to macro-level sustainability

In moving from step 1 and 2 to step 9, the technologies investigated must somehow be fitted into the macro-level of society. Even if the Ten Steps have not been and will not be formalised, agreed upon, or even developed adequately, the conceptual step to be made is to fit the micro-level of specific technologies into the macro-level where sustainability resides. The simplest way is to just equate improved eco-efficiency at the micro-level, as described in LCA-type models, with improved eco-efficiency at the macro-level and hence with improved sustainability. This is represented by the interrupted grey arrow in figure 3. This simple option 'by assumption' is clearly not satisfactory, but may be the only one available in many decision situations, and it is definitely better than no analysis at all. It may very well differentiate between relatively similar options, especially if the same time frames involved. The simplest quantification with a minimum of subjective assumptions is the maximum abatement cost (MAC) method (see Oka et al 2005; Ishikawa and Huppes 2006). Environmental improvements with lower cost, that is improved eco-efficiency is the simple result. Slightly more complex is the LCA analysis with the Life Cycle Costing Analysis added. For larger scale changes involving a longer time horizon, this MAC and LCA/LCC analysis is clearly insufficient, as the bio-energy example has shown.

The simplest types of modelling not only leave out relevant knowledge but imply internal inconsistencies as well. LCA-type models are specified independent of time, covering a virtual life cycle as an idealised steady state. In these models, the 'steel for the truck for the iron ore production for the steel for the car' is produced by the same blast furnace as the steel for the car. In actual fact, these two processes are substantially separated in time, by up to many decades, with further technology development inevitably having taken place during that time. The macro-level cannot even be specified in a full life cycle approach. The options are snapshots for a year, or, with some dynamics involved, for a series of years. Regardless of the way the macro-level is defined and modelled, the volumes of the technology system have to be quantified and fitted into the macro-level. Mathematically, this can be done elegantly, if both levels are defined in terms of linear equations (Heijungs 2001; Heijungs & Suh 2002). The incongruence, in modelling terms, between life cycle and snapshot might also be resolved by making the technology specifications dynamic. This complex endeavour has never been realised on a life cycle basis. The other option is to accept the inconsistency in time when fitting technologies into the macro-level IO framework.

Snapshots per year or for a series of years indicate how society would function under each of the alternative options. The absolute scores have limited value for decision support. It is the comparison between options with the relative scores to be interpreted. How would society function differently because of the decision being made? The empirical modelling steps are then all relevant. Regardless of the way one may deal with this modelling information and general background knowledge, the result can currently only be in terms of IO-modelling based snapshots. The snapshots may be the result of using current IO tables as models, with some technologies adapted and total demand kept constant. For current choices with a limited time horizon, this may already be a sophisticated option. They may be the result of the exogenous construction of technology scenarios ('low carbon society 2050'; see Fujino et al 2008), or they may be the result of a combination of modelling for all steps in the empirical analysis, framed in scenarios to cover the largest uncertainties for the longer term future. While the structure of the empirical analysis used to link specific technologies into a quantified IO framework remains the same, the normative analysis can be set up in many different ways. Economists may set up a discounted net present value analysis, passing by the eco-efficiency step. This has been done in climate modelling, resulting in complex discussions on discounting; see a good survey in Kopp & Portney (1999) and the introduction in Portney & Weyant Eds (1999). xxx

An application of the integration framework: the biofuels case

Do biofuels contribute to sustainability? The answer of course depends on the type of biofuel, on the biotic resources used, on the technologies employed to convert biomass into fuel, on the volumes and, from a different perspective, on the time scales to be considered. Regardless of the way ***Step 1, Framing questions,*** may be specified, given a set of specific options to consider, the answer also depends on the set-up of the modelling system and on the way in which the sustainability requirements assumed to be met are evaluated. The basic framework for analysis (see figures 1 and 2) then has to be specified, using the elements of figure 3. Simple types of analysis jump from simple micro-level analysis to sustainability conclusions. Since this is not adequate in this case, so let us go through the steps and see what has been done and should be done.

Step 2, LCA/LCC-type models, has been very well covered. The introduction of biofuels has been supported by LCA-type studies, not even explicit LCAs. They constitute the simplest type of models, and do not specify clear methods. Farrell et al (2006) have made a survey of US studies, reducing them to a common data format. These studies indicated a range of limited effects on CO_2 emissions, positive or negative depending on feedstock and the technology applied and, in a different perspective, depending on the background of the commissioner. Explicit LCA studies, with better defined methods, have led to similar outcomes; for a large review study, see Zah et al (2007). Next, a closer look at LCA methods shows that methodological choices, especially those regarding allocation methods, lead to differing and even contradictory outcomes, see Luo et al 2008a. Outcomes can also be greatly influenced by assumptions regarding emissions of N_2O, a potent greenhouse gas emitted from agriculture, diminishing the potential for climate change reductions in terms of only CO_2. The most positive LCA-type studies relate to second-generation biofuels, based on cellulosic feedstock, which cannot be used as food (except after biotic transformation, as into mushrooms like shiitake, or by ruminants, as into milk and meat). Technical assumptions about future technologies then may well lead to very attractive outcomes in terms of our technosphere relations with the broader environment. But will this future attractiveness be real?

Let us first have a look at the rapidly growing ethanol production from corn (as maize), a first-generation biofuel. Studies consistently aligning economic and environmental analyses, both on a life cycle basis, have so far been scarce, with Luo et al (2008b) as an early exception. How would such a technology score in terms of eco-efficiency? We use economic data from the Doornbosch & Steenblik (2007) OECD report. The costs of corn-based ethanol are subsidised to the market level of the competing gasoline, which has an excise on it, so corn ethanol is subsidised twice. The direct subsidy (in several forms) in the US is around $1.25 for the equivalent of 1 litre of gasoline, still much lower than in the EU, but well above the 2007 market price for gasoline of around $0.75 per litre. The cost of getting the ethanol on the fuel market, including profits, must therefore be around $2.00 per litre, but cost in this case is not value as the cost are higher than the market price. One part of this cost is covered by subsidies, another part by taxes on its gasoline competitor, and another by the cost of gasoline in terms of added value and scarcity rents. Taking the market value as a reference, the eco-efficiency of US bio-ethanol is of the same order of magnitude as that of gasoline, with optimists expecting a climate advantage of the order of up to 30%. Taking the real cost of production (= excluding transfer payments) as a reference, the eco-efficiency of biofuel becomes much better, even if the scarcity rent paid on oil is included. There is a difference of a factor of 4 with fossil gasoline, because corn is so much more expensive. In terms of the usual sustainability goals, there then is a ‘win-lose’ situation, that is, it is located in the lower right-hand quadrant in figure 4. The eco-efficiency is the slope of the dotted line, starting at zero environmental interventions (see our introduction in Huppes & Ishikawa Eds (2007a) for a fuller treatment of this technically tricky subject, with positive and negative values and inversion of the ratio). This shift towards the lower right-hand quadrant implies *degrowth*. Whether this is to be evaluated as positive or negative depends on precise E&E scores and on relative preferences regarding the economic and the environmental effects. This explicit analysis is implied but not explicitly stated in the available studies at the level of step 2.

Step 3, technical models, is currently the subject of much analysis. These models guide technology development, seeking improvements on energy requirements in transport and biochemical transformation, and looking for biomass sources with the most favourable environmental profile. These models indicate that substantial improvements in environmental performance are possible. Cost indications are less clear. For some time to come, only residues from production processes, for instance in sugarcane mills, pulp industries and timber mills, may be profitable without subsidies. The outcome of this analysis is that we should go for second-generation biofuel, based on waste or low-price side products or for cellulose grown on poor soils with little fertiliser, preferably processed in flexible biorefineries which can switch between inputs and can produce variable mixes of outputs. For the US, the choice then includes stover as a biofuel feedstock. This partly assumption-based theoretical analysis shows potentials which still remain to be realised in practice. Several studies have focused on this level, with links to land and water restrictions and markets (see Dornburg et al, 2008, for a highly comprehensive study). Kløverpris et al (2008) distinguish three approaches to land use. They describe the *LCA approach*, as developed in consequential LCA, which to some extent takes substitution mechanisms into account. The other two are the *economic approach*, which can specify step 4, and the *geographical approach*, which fits into step 5.

Step 4, micro-economic models, considers the main markets involved and how they will be influenced. What light can these models shed on the performance of bio-ethanol from corn? The 'main markets involved' is not a well defined category but offers considerable guidance. First, there are the market models of supply and demand in relation to the introduction of bio-ethanol. The first reasoned choice that has to be made is the choice of the volume of corn-based ethanol, in this case induced by policies, against operant market mechanisms which otherwise would lead to the fossil option. We assume the equivalent of 10% of the US gasoline market, which constitutes 40% of the global gasoline market. The first market involved is the food and fodder market for corn. Rising prices will shift demand to other staple foods and fodders, especially grains and soy, where prices will rise as well, as they already did aggressively with the much smaller amounts of corn now being used for ethanol. These are obvious markets. Next, however, there are more specific markets connected, which are not easily generalisable to broader classes of cases. In the bio-ethanol case, land markets are crucial, with environmental effects of land use changes a crucial factor in the eco-efficiency analysis, and crude oil markets. The increased demand induced by using corn for ethanol can be met in only two ways, by intensification and by area increases on formerly non-corn land. Increased supply will be based on both mechanisms. The environmental impacts have been studied with a focus on the conversion of land to agriculture in two Sciencexpress publications (Fargione et al 2008; Searchinger et al 2008). They decompose the forest clearing practices that are already occurring into a part due to increased food demand and a part due to fossil fuels; see step 5 for the constraint aspect. They link the land-use change to carbon emissions due the one-off change-over. This dynamic effect is difficult to fit into a comparative-static model, as is required in the approach developed here, but should not be ignored for such a practical reason. It is clear that the major shifts in food prices will have substantial further economic, social and political consequences, as farmers in the world will get richer and consumers will be hit, especially poor ones in the larger cities of the developing world.

A second main area of market effects has been ignored altogether, viz. the effect on the fossil fuel markets. Adding a new source of fuel supply will lower fossil fuel prices, to the extent that the shift does indeed takes place. Supply will then be reduced, but it will not be fully replaced by the biofuel. The lower price, lower than what it otherwise would have been, will attract other demand. With a long-term price elasticity of demand around unity, a one percent price reduction will lead to a one percent increase in demand. The elasticity of supply is less accurately known. In the short term, supply is quite inelastic, so hardly any displacement would occur. In the longer run, however, supply is much more elastic and some displacement would take place. One market mechanism is that of land markets required for the increased volume of the total production of bio-energy, biomaterials and food. This land-use market is characterised by a physical constraint, the amount of land available on earth that is fit for production, when conditioning factors like climate and water availability are taken into account; see step 5.

Step 5, physical models, goes into the physical constraints and options involved. Many new technologies, like solar cells, require rare metals whose production often cannot be easily increased. In the case of first generation bio-ethanol, however, this hardly seems to be the case. At the substance level, phosphate fertiliser may come to be in short supply, shorter than without biofuel. The intention for energy is to reduce dependence on fossil sources. As the effect will be very limited, there is no constraint here. The major constraint is in land available for production. The constraint is not a hard one, as land used for other purposes, especially wildlife areas, can be converted. This shift in land use due to market forces is taking place at a rapid pace, not only fuelled by energy policies and prices but also by rising food demand from an increasingly affluent global population.

Technically, we could grow all our food on a fraction of current land, with large tracts of land becoming available for biomass for energy, as IIASA studies have shown. The survey by Berndes, Hoogwijk en van den Broek (2003) focuses on potential as well, but indicates the large uncertainties due to complex interrelations with other agricultural activities. In most instances, however, there are no mechanisms in society to shift economic activities towards environmentally attractive options. Two recent studies referred to above, Fargione et al (2008) and Searchinger et al (2008), have analysed the empirical land-use shifts resulting from biofuel production, decomposing several mechanisms involved. The environmental effects can be very substantial, whether directly or through their influence on production functions. The effects of clearing forests are especially large in the case of wet peaty soils, as in many places in South-East Asia. After the initial conversion, often based on burning with heavy emissions, large emissions will continue till the peat layer is fully oxidised. The contribution to climate change is enormous, negating any small positive effects analysed in step 2 for many decades if not centuries to come. Linking this partial dynamic analysis to an overall comparative-static framework is possible only by using some assumptions on how the effects will be dispersed in time, with some rules on attribution. If second-generation biofuel is a transitional phenomenon, to be taken over by algae, wind and wave power and solar cells, the climate cost of this transition are very much higher than when a long life for second-generation is envisaged. In any case, taking this result into account leads to a ‘lose-lose’ situation, that is, the lower left-hand quadrant in figure 4. The eco-efficiency ratio is difficult to interpret in absolute terms, but the difference analysis with fossil can show the double negative score.

The land-use constraint can only be worked into the supply functions of all crops together, not specifically into those related to biofuel. The harder the constraint on land-use shifts, for example due to more effective land-use zoning laws, the more the increase in total biomass production will have to be gained on the given area, leading to more intense agriculture. This not only has direct effects on biodiversity in areas used fro these ***other*** agricultural activities but also leads to increased emissions there of N_2O, a potent greenhouse gas (GWP_{100} = 310). Even the more comprehensive studies being set up, like that by the Royal Society (2008), by the OECD (Doornbosch & Steenblik 2007), and by Dornburg et al (2008), do not mention this mechanism.

Next, ***step 6, meso/macro-economic models***, covers the knowledge gained from general equilibrium models as have been developed especially for energy policy purposes. The EU's biofuels policy has been based on this level of analysis, incorporated in official impact assessments using economic models for the European energy market, PRIMES and GREEN-X; see CEC 2006 and 2007. They show substantial reductions in European emissions of climate gases, assuming the use of set-aside lands and not considering secondary effects. However, they are not technology-specific, do not take into account more comprehensive market mechanisms and do not cover physical limitations. Neither do they cover a broader set of environmental concerns. They do show, however, that there are economic and technical options for producing biomass for biofuel in Europe, whether attractive or not.

Step 7, socio-cultural models, is the least amenable to modelling. Empirical assessments may diverge widely. Optimists could paint a better future thanks to induced agricultural development, while pessimists may see a world breaking up as governments cannot meet the demands of the poor masses. While these considerations are clearly relevant, the point is how to narrow them down, preferably by reasoned expectations and otherwise by scenario assumptions. As with technology modelling, it is well possible to state conditions for sustainable use of biomass for energy, and frame them in scenarios. This approach has been followed in Dutch policy development. The Cramer Commission (2007), established by the current Dutch minister for the environment and responsible for implementation, specified criteria like 'Biomass production must not affect protected or vulnerable biodiversity and will, where possible, have to strengthen biodiversity.' (p III), with a certification system at origin to safeguard this. Such a certification system would inevitably ignore broader market mechanisms and other secondary mechanisms. Looking only at the mechanisms set in motion, not the adjoining policies, is difficult enough in itself. Developments like the nature conservation legislation now being introduced in Indonesia are triggered by disaster, but still: triggered. In the long run, such developments might be of prime importance. There is a clear gap in our ability to deal with these cultural, institutional and political mechanisms, not only in the case of biofuels.

The environmental models relevant to the analysis, covered in ***step 8, environmental models***, could at first be the ones developed for LCA, linking environmental interventions of activities to *midpoints*, as intermediate environmental mechanisms, and then possibly to endpoints. For biomass and biofuel production, these include at least climate forcing or climate change, eutrophication, acidification, ecotoxicity and human toxicity. These and more direct mechanisms can be used to indicate the endpoints for evaluation, like biodiversity and more comprehensive environmental quality, human health and the more general life support functions of the environment. In the case of the conversion of wildlife areas to crop land, new environmental mechanisms were developed in the research papers by Fargione et al (2008) and Searchinger et al (2008), with more location-specific models. Such case-specific additions may be very useful in gaining new perspectives, but it is hard to establish rules about when and how to develop them. In this case, the huge Indonesian emissions (Indonesia being the world's third emitter of CO_2) give some indication of what to look for.

We now arrive at the integrative ***step 9, hybrid IO models***, covering the micro-level in a macro-economic context. Let us assume at this stage that technology supply has become more rational, that major market effects have been covered, and that a land-use model taking land availability into account is part of the biomass supply function. This is not yet the case, but might be developed without too much trouble. Furthermore, general equilibrium models have an input-output kernel which is conceptually equal to the models of step 9, though generally too aggregate to be linked to detailed environmental interventions. These are all partial or highly aggregate models, with some interrelations. Combined with the technology system description, these form the main inputs in setting up the input-output model with an environmental extension framework, including adjusted emission coefficients. The large non-linearities involved, especially in land use, are squeezed into the linear modelling structure. Land-use shifts can be dealt with by comparing the scenarios with and without bio-ethanol. The environmental impacts are reflected in adjusted coefficients, with the one-off land-use change effects still in a separate box to be dealt with, or allocated over a certain period of time.

However deep and rich the modelling used to fill the hybrid EIO models in step 9 may have been, some specific subjects need attention when specifying the future functioning of the economy. One issue, which is important in the biofuel case, is the choice of whether to use factor cost or market prices in quantifications, or both in parallel. One major difference is the inclusion of taxes and subsidies, as transfer payment. The special situation of biofuels is that they are heavily subsidised in several ways, from direct grants and import restrictions to feed-in tariffs and obligatory market shares, as by mixing with fossil fuel. The last of these mechanisms represents an indirect subsidy paid directly by the user, not by government, un unusual case for analysis. The subsidies are used to shift productive capacity from other products to bio-ethanol, decreasing production in the production chains of these other products. In the IO-type linear technology model, this will then lead to reduced environmental impacts in the rest of the economy. Overall production value decreases, representing de-growth (in constant prices), while overall environmental impacts hardly change; see option 2 in figure 4. Societal eco-efficiency, as the environmental intensity of production/consumption, therefore becomes more unfavourable, at a lower production level. This hardly seems the right way to go. Just decreasing production by working less would have the same economic effect, viz. degrowth, but then with more leisure, while the environmental impacts would then also decrease by roughly the same amount. This is a clear case for reasoned degrowth as an alternative to biofuels.

Finally, ***Step 10, combining empirical and normative analysis***, has not been actively specified at all. The links to different specific effects, as on economic development, several distribution aspects and several environmental aspects, has not yet been made in empirical studies. So even at this disaggregate level, the normative analysis is required to present results in a coherent fashion, e.g. as an environmental index based on weighted scores. The next step, integrating the different domains of sustainability, has been discussed in general, but hardly at this case level. Any reasoned decision will have to deal with this still very open subject.

One general concluding remark needs to be made on the outline for the relevant ideal full-case study. The large-scale policies to stimulate bio-ethanol in the US and Europe seem to have led to consequences which have hardly been covered in the preparatory studies till now. Studies could easily have investigated the additional demand for corn for ethanol, with land-use shifts towards large-scale corn production, and the reduced amounts of other staple foods produced as a result. The price rise in all staple grains is an easily quantifiable consequence, with poor populations in cities in developing countries suffering most, of course, and producers reaping profits. Also, such rising prices have induced large-scale development of tropical agriculture, not only for biomass-for-energy production but also for other products whose prices have risen. This expansion is more difficult to quantify but of course has led to serious loss of natural habitats and wet peaty soils, as in large parts of Borneo. Second- and third-generation biofuels, with different feedstocks, might have fewer negative effects, but this has not been investigated by analysing the mechanisms involved. The interesting question now is: why have we not foreseen such consequences of combined European and US policies, placed against a background of already rising prices due to growing populations and growing affluence, with increased demand for meat in China and other fast developing countries?

The simple answer seems to be that what is missing is a framework for such an analysis, not the will to make it. With hindsight, studies are now being undertaken to correct for some of the deficiencies in previous studies, taking into account the mechanisms which previous studies supporting biofuel policies had missed, by considering more complex effect mechanisms set in motion. To date, no study is available which covers all relevant mechanisms, let alone covering them in an integrated, quantified way. This seems a poor basis for a large-scale sustainability policy regarding biofuels, and bioenergy in general.

Eco-efficiency, eco-innovation and degrowth

The two main approaches for preventing further environmental degradation are technological improvement, that is *eco-innovation* with improved macro-level eco-efficiency, and *degrowth*, that is, producing and consuming less, together covering the IPAT equation. There are intricate links between these two options. Eco-innovation at a micro-level will usually contribute to economic growth at a macro-level, though not in a straightforward way. Degrowth, that is, reduced production and consumption, can reasonably be achieved along two lines. One is by fewer hours worked, with a shortened working week and including fewer people working. This could be part of a cultural development towards a slower, more leisurely society. As production equals consumption, disregarding net capital formation, the population times affluence part of the IPAT equation can be described as income or as consumption, with degrowth for a given population meaning lower affluence, relative to the reference. This links to the customary distinction between national income and national product. The other approach to degrowth is by taking environmental measures, improving the environment at the cost required to do so. In this case, there is a technological development towards the lower right-hand quadrant in figure 4. Less attractive options are to be found in the realm of crises and disasters reducing total production and consumption. Environmental improvement combined with growth requires improvements in technology, in terms of eco-efficiency, well beyond what has been achieved so far. The bulk of environmental improvement has been achieved through end-of-pipe measures or prohibiting measures, which by necessity increase cost, that is, degrowth in the lower right-hand quadrant of figure 4.

As regards environmental improvement, the choice is between the two approaches. The higher the growth, the higher the requirements on eco-efficiency. Even with active degrowth, higher eco-efficiency is attractive, as it reduces environmental impact for any level of consumption. How can we improve eco-efficiency, as a process of ***eco-innovation***?

Let us start with a few definitions to further clarify the role of eco-innovation and link it to the domain of technologists. This is not a new subject but a slightly different approach to the same subject covered in the IPAT analysis and in eco-efficiency.

Innovation ***is a change in economic activities that improves the overall performance of society across the economic and environmental dimensions of sustainable development.***

Eco-innovation ***is a change in economic activities that improves both the economic performance and the environmental performance of society.***

We leave lut the social aspects here. Eco-innovation is thus a subclass of innovation, leading to absolute decoupling, that is, the green surface in figure 3, if the figure is interpreted at the macro-level. Innovations that are not eco-innovations are characterised by economic improvements with environmental deterioration or environmental improvements with economic deterioration. The latter constitutes soft decoupling, based on some overall welfare considerations where environmental improvements can compensate for economic deterioration and vice versa. The curved line represents some normative view on how the trade-off is made. At any moment in time, technologies are given and the available options for production are limited. This production–possibility boundary is not in the figure, as the essence of the analysis here lies in not assuming a given set of technologies. If society improves its eco-efficiency, that is, achieves a less steep slope of the dotted lines, it can have a higher affluence with given environmental effects, a better environmental quality with given affluence, or a certain improvement in both, as eco-innovation. The current drive towards biofuels is the unpleasant version of degrowth. Only optimistic dynamic views on induced technology development with a high eco-efficiency may justify the current first-generation policies. But second-generation biofuels are not necessarily so eco-efficient either. If based on maize stover (see Luo et al (2008a)), the optimism can hardly be justified. We put the slow-drive movement (nr 1 in figure 4) as leading to a higher eco-efficiency at the macro-level of society. This corresponds to gut feeling, but would still have to be substantiated by research.

Around here:
Figure 4 Eco-innovation as a subclass of innovation

Knowing how an eco-innovation affects eco-efficiency, affluence and environmental quality is just one accomplishment. The other is how to steer development in the right direction. The decomposition analysis of statistics using variants of the IPAT equation, as has been done by Waggoner & Ausubel (2002) and York, Rosa & Dietz (2003), takes one step in the direction of a causative model which might be used instrumentally. As there is no broader conceptual framework involved than identities, the underlying causalities will not easily emerge. A more theoretical and hence strategic approach was followed for example by Fischer-Kowalski & Amann (2001), focusing on structural developments in the global economy. The theory of society may not exist, but some overarching framework may be chosen as a starting point. The main concepts and approaches used here are a distinction between culture, institutions and polity, together driving the economy, within the boundaries of the physical as reflected in the technosphere; see figure 1. The basic drivers of economic development is institutions, as these create the drivers of economic development. This is the broad consensus among economic historians like North, Freeman, Louça and Mokyr. The malleability of the economy is increasing due to a shift away from physically embodied economic growth to knowledge-based growth; see Romer (2007) as one of the originators, as well as the very readable survey by Warsch (2006) and the more scientific survey by Helpman (2004). The capacity for knowledge creation and use has developed to such an extent that the right incentives could easily induce developments. This is the optimistic part on how to steer towards eco-innovation.

Thus, the key to sustainable technology development seems to lie in creating institutions, including stabilised general policies for sustainable development. Sadly, there is not much there yet, nor is there much in the pipeline. The tradable permit system following the Kyoto protocol seems leaky in its control of carbon flows, and is not really being implemented, partly due to US and Chinese abstinence. Fitting environmental considerations into the same driver of economic decisions seems essential. Since property rights form the core of the incentive structure, environmental considerations would have to be translated in such terms. The old, now much watered-down, OECD principle was that *the polluter pays* for the direct damages he causes. This begs the question how to effectuate this in the realm of property rights. Leasing environmental property rights to users is one approach being developed; see Dalhammar (2007), especially Ch 4. Whatever will be set up as institutions in due time, it will have to take account of the task of reducing our negative impact on the environment, as indicated by eco-efficiency analysis.

Cultural change is often advocated as a means to change economic behaviour. The prospects for direct substantial influence seem limited. A sustainability analysis for local movements, local production for and by local communities, is still lacking, especially as related to land-use requirements. Higher income groups in the world might like to work less and consume less, but this is extremely difficult to achieve within current institutions, regularly reinforced by growth-oriented policies. Instead of stimulating early retirement, the richest countries want to increase life-time working hours. Reduced working hours seems the most feasible option for sensible degrowth now, and is fundamentally right. More comprehensive cultural change towards environmentally friendly and high-quality products seems a small niche, dampened by the big mass of indifferent consumption. The route through policies seems the most promising, as collectively adapted behaviour seems essential. This may involve policies for adjusting institutions (see above) or more ad hoc policies, like saving a wildlife area by turning it into a reserve, or subsidising the development of specific technologies. Though these are definitely useful, and may well be the best options for now, one can hardly imagine that such specific measures will change the course of economic development very much. Perhaps the realisation that win-win is not enough, that the environmental gain should be substantially larger than the economic gain, is one main contribution eco-efficiency analysis can make to policy development.

Conclusions

1. Eco-efficiency is an instrument to help direct decisions towards sustainable development, focusing on economic and environmental aspects. Regardless of how exactly sustainable development is defined, the defining elements should be reflected in eco-efficiency, since easy options like less materials, cradle-to-cradle, and biobased society will not work.
2. Eco-efficiency can be defined in absolute terms, or relative to a reference situation. The ultimate reference in strong sustainability is absolute in terms of ecological quality and a reasonable basic income for all, both definable from a general societal point of view.
3. There is no easy link between micro-level decisions and this ultimate macro-societal reference. This is because of time delays, problems with empirical modelling and the ill-defined nature of what constitutes environmental quality and a reasonable income and income distribution. Most win-win situations at a micro-level either will not work or may well be detrimental to environmental quality due to the implied economic growth.
4. It is impossible to construct one overarching model which combines all normatively relevant items of sustainability, even though relevant partial knowledge is available in many domains. This paper has developed a general framework in which several domains are placed in mutual perspective. It can be used as a checklist-like procedure.
5. The volatility of judgements, the incommensurate nature of the main characteristics and the indeterminate nature of social and physical dynamics make the outcomes of sustainability analysis in general and of eco-efficiency analysis in particular soft, even if expressed in hard numbers.
6. As decisions are being made anyway, creating our future, a reasoned choice is to be preferred to haphazard and mutually inconsistent choices. Reasonability requirements such as those formulated by Arrow and by Sen for collective decision-making apply to sustainability reasoning as well. They require explicit formulation of what is relevant and why, even if both can be stated only tentatively, and no effective general decision rules can be formulated.

7. Partial analyses, focusing on resource extraction, climate change, toxicity or income distribution, are all highly relevant but only if placed explicitly in the larger framework of sustainability analysis, using some form of integration of partially related and partially incommensurate but highly relevant elements.
8. Eco-efficiency analysis focuses on the technosphere, as the link between society and the natural system. The primary analysis relates to technologies. However, decisions on technologies are not just technical. They are shaped by culture, in terms of knowledge and values, by institutions and by political decisions, directly and through the cultural and institutional domain. The ultimate driver is culture. Eco-efficiency can indicate the possible role of technologies in moving towards decoupling and more comprehensive sustainability. There are good reasons to assume that technology is essential but cannot fix the problem alone, given the large and growing world population and the affluence aspirations of the developing world. Cultural shifts, leading to lower consumption by higher income groups, are then required globally to complement eco-efficiency improvement through technology development, and while hopefully being attractive in themselves as well.

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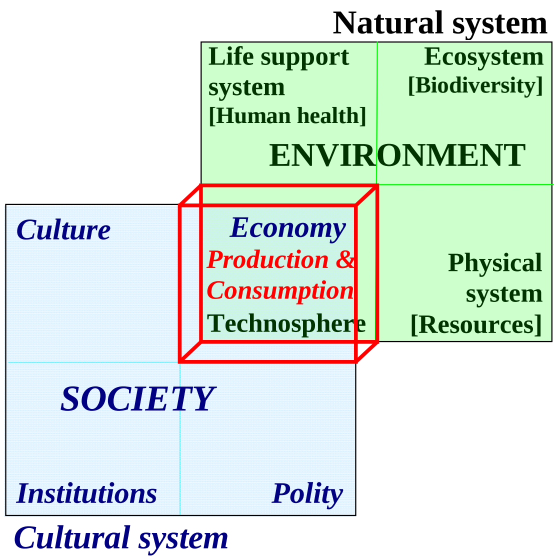
Figures [Color for web version, black-and-white for paper version]

Figure 1 Technosphere linking Environment and Economy



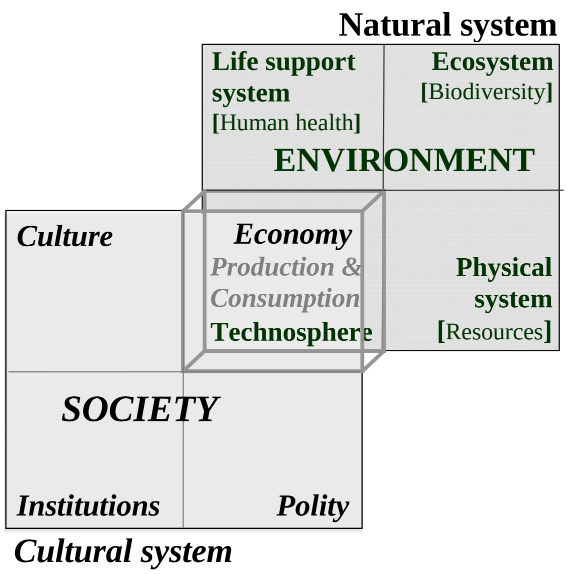
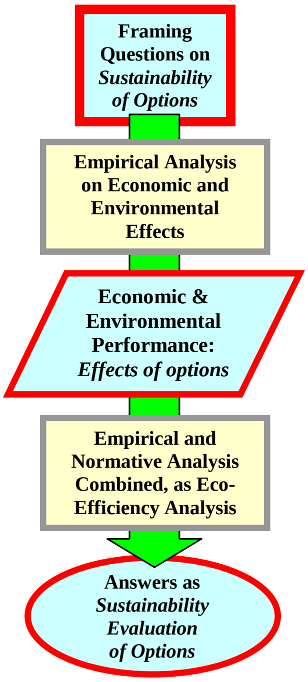


Figure 2 Sustainability evaluation through linked empirical and normative analyses



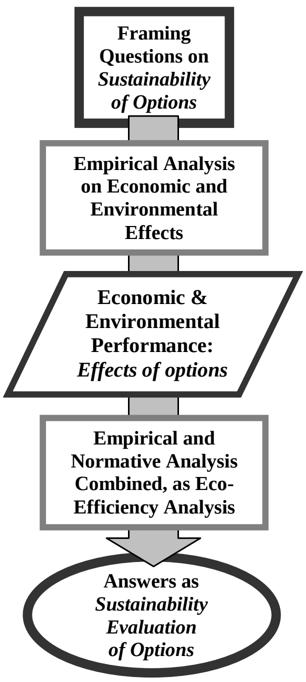
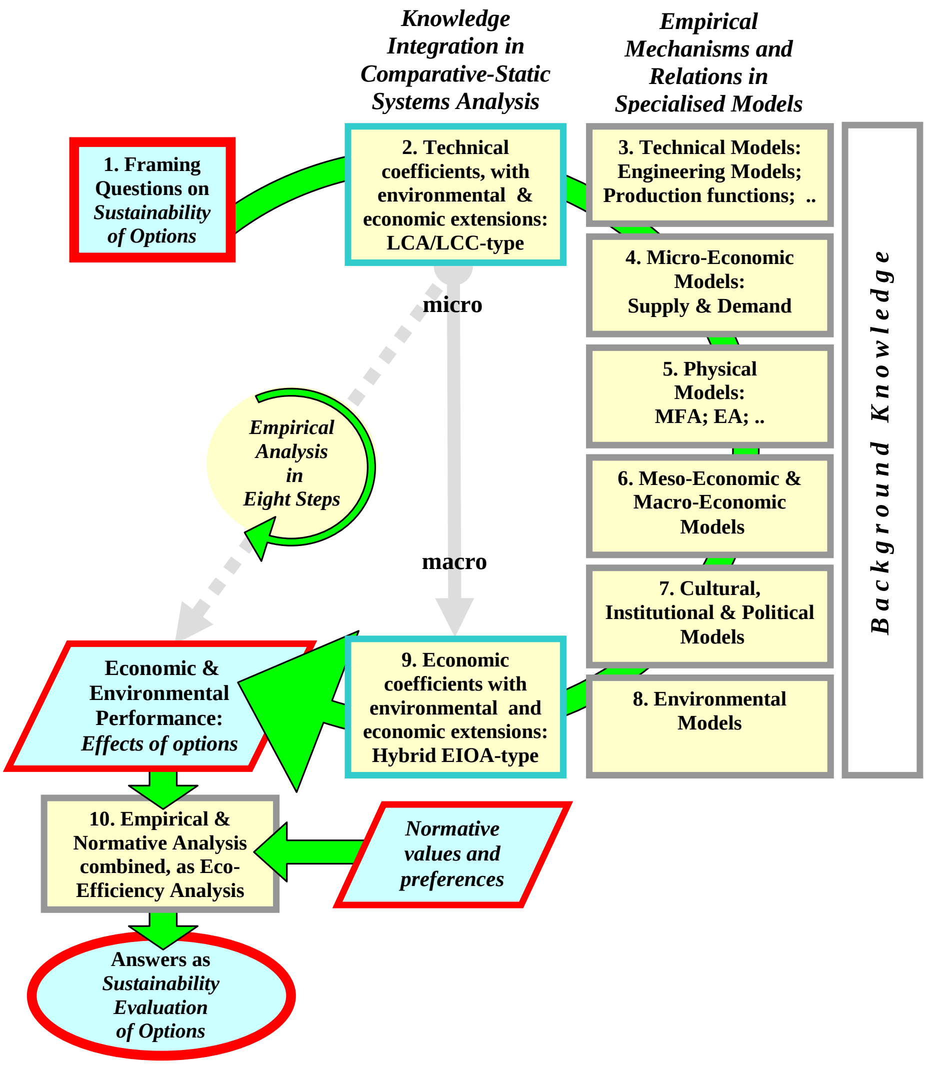
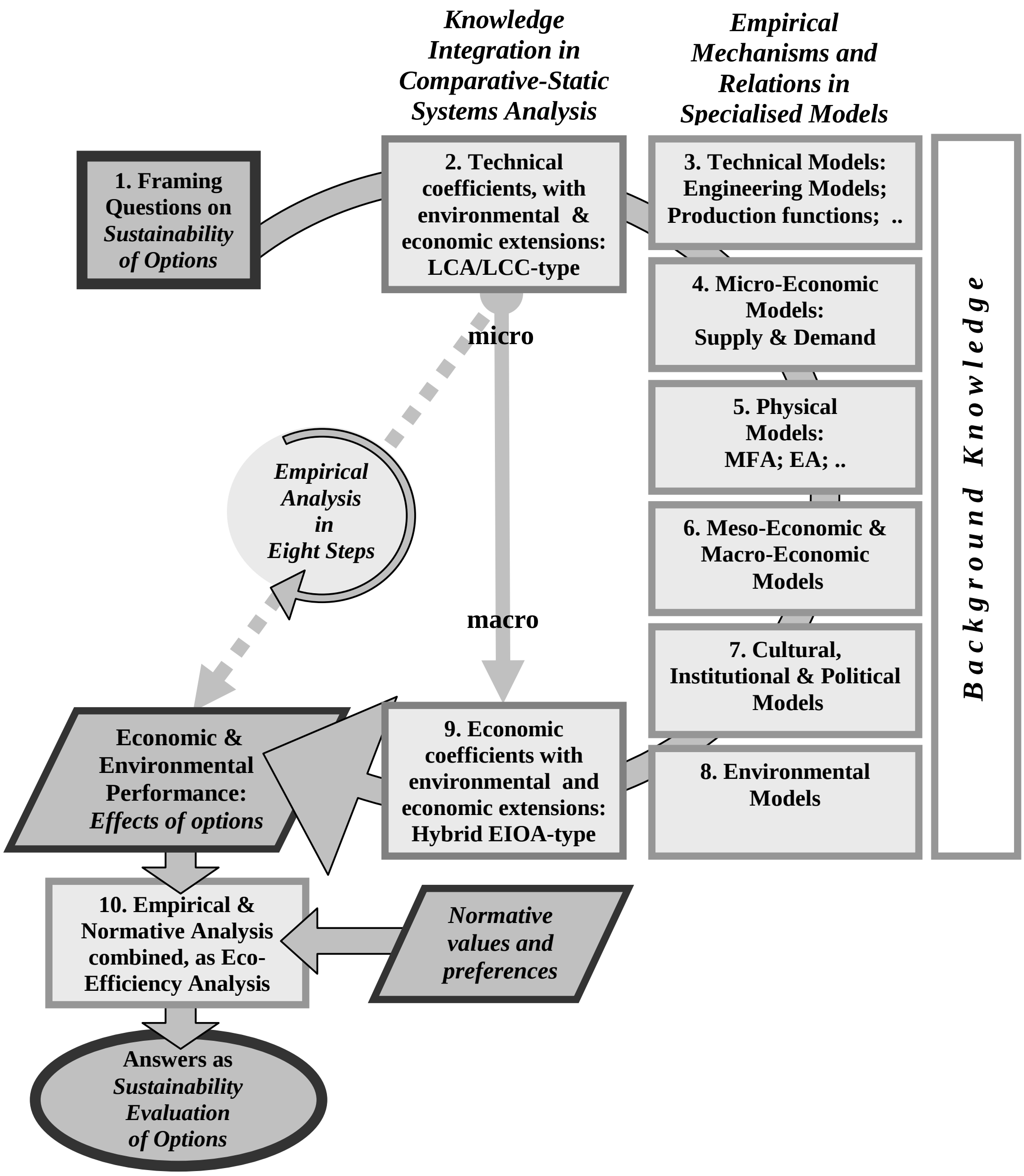


Figure 3 Ten basic steps in sustainability analysis of technology options.




Knowledge Integration in Comparative-Static Systems Analysis
Empirical Mechanisms and Relations in Specialised Models
1. Framing Questions on Sustainability of Options
2. Technical coefficients, with environmental & economic extensions: LCA/LCC-type
3. Technical Models: Engineering Models; Production functions; ..
4. Micro-Economic Models: Supply & Demand
5. Physical Models: MFA; EA; ..
6. Meso-Economic & Macro-Economic Models
7. Cultural, Institutional & Political Models
8. Environmental Models
Background Knowledge
micro
macro
Empirical Analysis in Eight Steps
9. Economic coefficients with environmental and economic extensions: Hybrid EIOA-type
Economic & Environmental Performance: Effects of options
10. Empirical & Normative Analysis combined, as Eco-Efficiency Analysis
Normative values and preferences
Answers as Sustainability Evaluation of Options

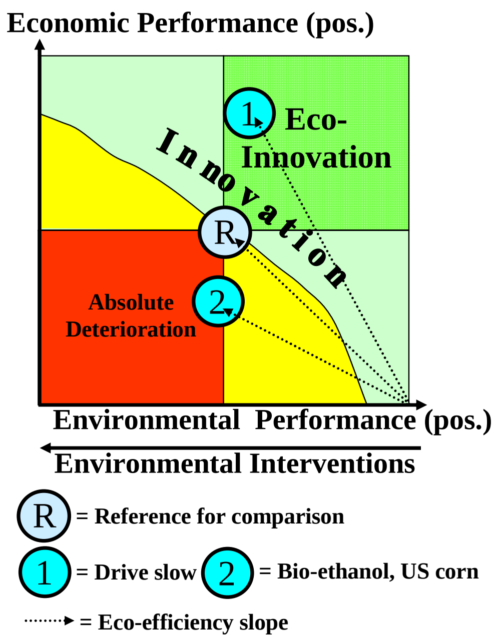


Figure 4 Eco-innovation as a subclass of innovation