Technological Environmental Innovations

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Abstract

This paper is based on empirical research on a taxonomy of technological environmental innovations. It draws on a databank with over 500 examples of new technologies (materials, products, processes and practices) which come with benign environmental effects.

The approaches applied to interpreting the datasets are innovation life cycle analysis, and product chain analysis. Main results include the following:

1. Innovations merely aimed at eco-efficiency do in most cases not represent significant contributions to improving the properties of the industrial metabolism. This can better be achieved by technologies that fulfill the criteria of eco-consistency (metabolic consistency), also called eco-effectiveness.

2. Ecological pressure of a technology is basically determined by its conceptual make-up and design. Most promising thus are technologies in earlier rather than later stages of their life cycle (i.e. during R&D and customisation in growing numbers), because it is during the stages *before* reaching the inflection point and maturity in a learning curve where technological environmental innovations can best contribute to improving ecological consistency of the industrial metabolism while at the same time delivering their maximum increase in efficiency as well.

3. Moreover, environmental action needs to focus on early steps in the vertical manufacturing chain rather than on those in the end. Most of the ecological pressure of a technology is normally not caused end-of-chain in use or consumption, but in the more basic steps of the manufacturing chain (with the exception of products the use of which consumes energy, e.g. vehicles, appliances).

There are conclusions to be drawn for refocusing attention from downstream to upstream in life cycles and product chains, and for a shift of emphasis in environmental policy from regulation to innovation. Ambitious environmental standards, though, continue to be an important regulative precondition of ecologically benign technological innovation.

1. Technological Environmental Innovations (TEIs) and Metabolic Consistency

Environmental innovation includes any kind of innovations – technical, economic, legal, institutional, organisational, behavioural – that lead to an improvement of ecological quality, regardless of any additional advantage or motive (Klemmer et al. 1999 25, also Hemmelskamp/Rennings/Leone 2000).

This paper just deals with technological environmental innovations (TEIs). A technology is a body of knowledge, especially know-how, but also includes some theoretical know-why as well as know-what-for (also Freeman 1987 235, Kemp 1997 pp7). As far as know-how is concerned, a technology is a method of applying a specific knowledge base for achieving a specified operative purpose by special operative means such as tools (instruments, materials, machinery, plant equipment, infrastructures) and practices. Products – as much as production processes and services – are specific instrumental manifestations, or apparatus-like implementations of a technology. Products, processes and services tend to be marketable, commercialised applications of a technology.

In order to qualify as a TEI for entry into the database of this study, technological innovations had to meet one or several aspects of the environmental innovation strategies as listed in Table 1.

Table 1 Selected concepts of technological environmental innovation according to the realm of innovation where they most apply

Realm **Approach**	Energy incl. vehicles propulsion, heating	Raw materials. Natural resources	Agriculture	Chemistry, Chemicals	Materials processing and reprocessing	End-products: Building, vehicles, utility goods	Emissions control, waste processing
Industrial symbiosis. Zero-emission processes. Circulatory economy	x	x	x	x	x	x	x
Sustainable resource management	x	x	x	x	x	x	
Cleaner technologies	x	x	x	x	x	x	
Benign substitution				x	x	x	
Product design for environment				x	x	x	
Bionics				x	x	x	
Add-on purification technology							x

Another, and perhaps more coherent way of deciding whether a technological innovation qualifies as an environmental innovation, is to determine whether a new technology or product contributes to significantly increasing eco-efficiency and/or improving ecological or metabolic consistency. These terms are closely linked to the sustainability discourse and to the concept of industrial metabolism (Ayres 1996), or industrial ecology respectively. Criticism of the shortcomings of the previous sustainability discourse has been a key element in the more recent discourse on ecological modernisation (Andersen/Massa 2000, Mol/ Sonnenfeld 2000), and within this context it was the starting point of the concept of ecological or metabolic consistency (Huber 2004, 2000), sometimes also referred to as eco-effectiveness (Braungart/McDonough 2002 103–117).

Metabolic consistency focuses on the structural, qualitative side of technology, not just input-output-quantities within basically given structures. Ecological consistency is about how to re-embed the industrial metabolism within nature's metabolism by introducing new technosystems, regimes and practices, thus changing technological structures and the metabolic qualities of products and processes, rather than mere quantity of turnover within old structures. E.g., energy demand on giga and tera levels may not be an ecological problem as such if the energy were based on clean fuels such as hydrogen, or represented fuelless energy from solar, wind, hydro and geothermal sources. Whereas an efficiency approach primarily appeals to green savings commissioners, a consistency approach calls for green inventors and investors.

In terms of various lines of ecological discourse, TEIs can thus be characterised as being the operative tool-set of technological regimes aimed at ecological modernisation, i.e. structural change towards benign or at least strain-relieving effects on resources, sinks, ecosystems and the biosphere. TEIs eliminate, or reduce, or help to control environmental hazard (risk). TEIs create metabolic consistency and optimise eco-efficiency. TEIs can be add-on as well as integrated, although integrated solutions are in almost any case preferable from an ecological point of view.

2. Collection of TEIs and database

The criteria of TEIs and its systematics emerged in the course of long-standing empirical research, which has from 2001 to 2004 also been carried out in connection with the Key Environmental Innovations group of the German Federal Research Ministry's Initiative on Sustainability and Innovation. An explorative databank has been created which now numbers 305 datasets, with a total of more than 500 examples of TEIs.

Corresponding to the approaches of innovation life cycle analysis and product chain analysis, the datasets include information on a technology (products, materials, processes, practices), its structural impact, the life cycle stage of development and diffusion, on rival like technologies, competitiveness and adoptability, as well as ecological properties and environmental improvements which have been achieved or can be expected.

The databank has been fed by a continuous survey of innovations as they were reported in articles in a number of specialised journals and newsletters (among these MIT Technology Review, The Economist and The Economist Quarterly, VDI Nachrichten) from the beginning of 2000 through to March 2003.

3. Some examples and trends of TEIs

Typical examples and trends of TEIs include the following. They all represent innovative regime shifts from mature conventional technologies to new ones that are metabolically more consistent, and normally also much more efficient than previous like technologies:

- Replacement of fossil fuels with clean-burn hydrogen, the use of which does not require additional end-of-pipe purification of emissions
- Substitution of clean electrochemical fuel cells for pollutant furnaces and combustion engines in manifold applications, from power stations to vehicle propulsion
- Clean coal, notably in zero-emission central power plants on the basis of IGCC technology (integrated gasifier combined cycle) and CO_2 sequestration. The purpose of these power plants is to produce hydrogen by steam reformation as much as to generate electricity.
- Fuelless energy such as photovoltaics and further regenerative energies which make use of sun radiation, geothermal flows, or wind and water currents
- Decentral micropower, i.e. new sources of electricity generation that are leading towards distributed power generation (which includes a certain number of large central stations). Over-centralised power generation and one-way distribution will thus be replaced by an integrated two-way-flow grid management.
- Transgenic biochemistry which makes use of enzymes and microorganisms especially designed and bred for various production tasks, thus replacing the conventional high-temperature high-pressure chemistry that poses a heavy burden on the environment and human health
- Substitution of high-hazard chemicals for more benign low-impact substances and new specialty chemicals which are, among other things, biodegradable, non-persistent, non-accumulative and non-toxic
- Biofeedstocks replacing petrol as a raw material to a certain extent
- New materials which are simultaneously ultra-light and ultra-strong, saving larger volumes of conventional materials and energy
- Micromachines and nanotechnology which relieve pressure on resources and sinks compared to larger conventional machines and chemical production
- Substituting sonar, photonic and microfluidic analyses for cumbersome conventional methods involving many hazardous ingredients, and thus considerably improving quality and performance of production
- Circular production processes in which water, auxiliary substances, metals, bulk minerals and fibres are recycled at an optimum rate
- Last but not least, overcoming the ecologically devastating practices of today's over-intensified and inappropriately chemicalised agriculture by introducing sound ecological practices in combination with high-tech precision farming and, again, modern biotechnology which makes use of transgenic organisms.

Since biotechnology is a sensitive issue, it may deserve a brief comment: genetic engineering in agriculture, as well as transgenic biotechnology in chemistry, nanotechnology, materials processing, waste management, pharmacology and medicine, has to be considered as an important field of TEIs, full in the knowledge that such an assessment will certainly remain controversial for another one or two decades to come. As tends to be the case with true key innovations of major structural importance, people's sense of security is undermined. Conservative opposition and risk aversion are strong. It takes time to replace uncertain expectations with realistic experience. Not all feelings of uneasiness are unfounded, but in most cases it has turned out that in fact they were. Almost all transgenic innovations seem to spur efficiency, and most of the examples represented in the database are environmentally benign in that they allow to substitute, e.g., for conventional high-temperature high-pressure processes, hazardous chemicals, resources input and emissions output. Biotechnologies improve on productivity and product quality. In comparison to these advantages, fears of particular disadvantages are dwarfed, or are untenable in face of the facts. But not all applications – such as pesticide-resistant crops – can be said to be metabolically consistent. Some are not, or not yet.

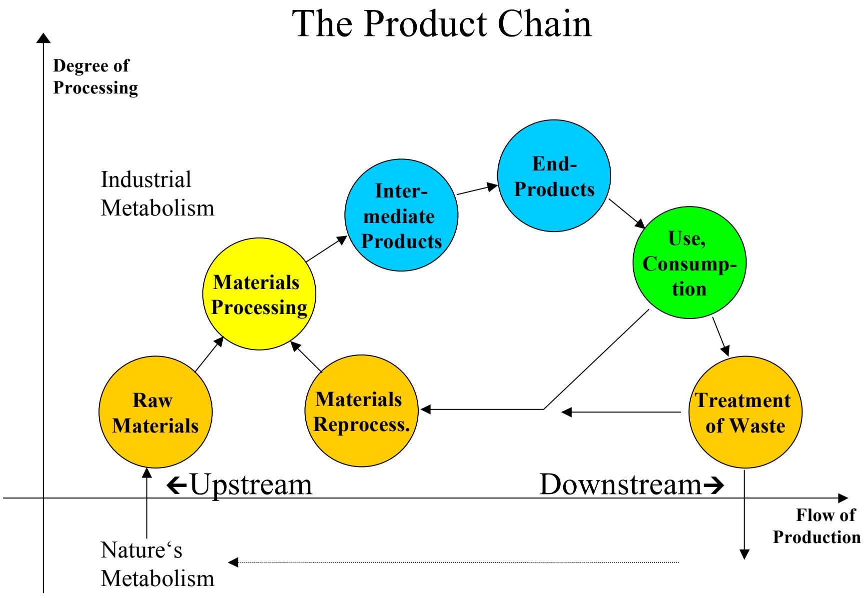
4. TEIs tend to be upstream the product chain and upstream a technology's life cycle

In terms of integrated solutions versus add-on measures, 85% of TEIs in the database represent integrated solutions, 15% environmental add-on technology. This is hardly surprising, serving to confirm what was to be expected. Of the 85% integrated solutions, 49% can be said to be driven mainly by ecological motives so that these are TEIs by prime intention, whereas in 36% of the examples ecological motives, though these may also be considered, cannot be said to be the main reason behind that innovation.

The central finding which emerges from the present investigation is that most TEIs, and also the most important TEIs in terms of structural impact, tend to be upstream in the manufacturing chain, and upstream the learning curve in the life cycle of a technology or product. The upstream tendency of TEIs is all the more true if we consider energy technology to be upstream in any production function in that it is a primary basic input component at each step in the manufacturing chain.

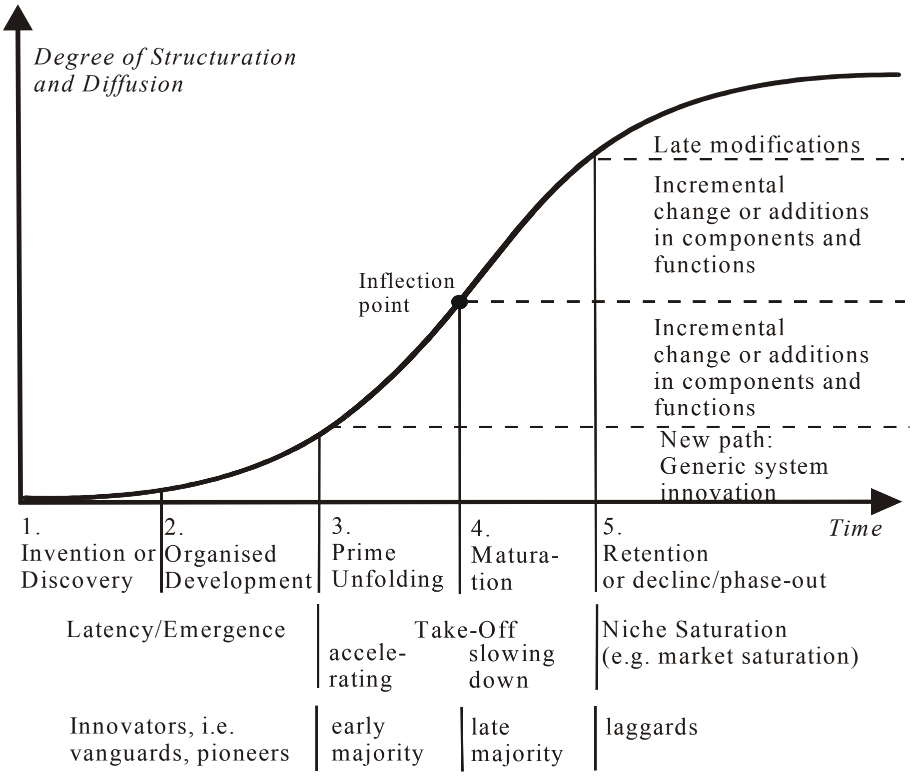
In the environmental literature, the term 'life cycle analysis' is often used interchangeably with 'product chain analysis' or 'eco-balances' that try to gauge the environmental impact of a product from first input by extraction of raw materials to last output by being definitely phased out as waste. What they represent more precisely, however, is analysis of the vertical manufacturing chain or product chain as shown in Figure 1. By contrast, another meaning of

Figure 1 The product chain



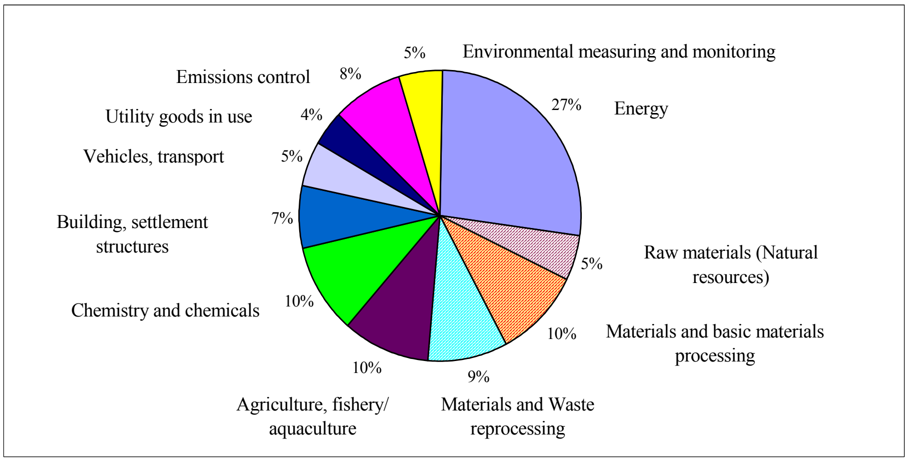
life cycle analysis refers to an innovation life cycle or technology life cycle as shown in Figure 2, i.e. the evolutive existence of a technology or product species.

Figure 2 The innovation life cycle



As can be seen in Figure 3, more than a quarter of the datasets (27%) relate to energy, including vehicle propulsion and energy design of buildings (not however innovations related to energy demand of appliances). The number of TEIs in the realm of energy is matched only by 24% of technologies relating to the extraction, processing and reprocessing of materials, which accounts for 34% if agriculture is included, and 44% if TEIs in the realm the chemical industry, 52% if emissions control is added to this.

Figure 3 TEIs according to realm of innovation (n = 298)



We can try to specifically ascribe energy technologies and emissions control to the sectors where they actually occur within the vertical manufacturing chain. We can thus make a distinction between end-products on the one hand, and intermediate products, and primary or base products, both representing pre-products, on the other hand. We can furthermore distinguish user or consumer behaviour (practices) from producer practices (behaviour and regime rules). We again exclude TEIs regarding off-site measuring and monitoring. This results in the categories of (a) primary or base production and materials, (b) materials processing and intermediate productions, (c) final productions and products, and (d) user behaviour or consumer practices as shown in Table 2.

In this way the upstream concentration of TEIs emerges even more markedly. Primary productions and base products represent the biggest slice with 44%, materials processing and intermediate products 27%, making up 71% of the TEIs in primary and intermediate productions. Final productions and end-products represent 25%. Most of this relates to building and vehicles rather than office and household appliances and consumer goods. By contrast, innovative practices regarding consumption and private user behaviour (such as soft driving, car-sharing, leasing instead of buying, avoiding overheating of rooms, etc.) at 4% do not count for much. Even if this figure were doubled or tripled, the finding and its message would basically remain the same: TEIs are upstream rather than downstream in the manufacturing chain.

As a rule of thumb one can say the more products and production processes are placed chain-upwards, the more important the potential of their environmental impact is. This is particularly the case with regard to the difference between all of the steps of extracting and successively (re)processing materials, which regularly cause large environmental impact, and the final assembly or finishing of final products, which causes comparatively less impact. In the same sense it can be said that it is the processes of production rather than the use of products which cause environmental impact.

Table 2 TEIs (products, processes, practices) according to chain position

Primary productions or base products e.g. raw materials, primary fuels, power stations, agriculture, forestry, base materials (steel, cement, pulping, tanning, …), secondary raw materials from recycling, also incl. related add-on-purification technology	Pre-products and pre-producer practices 71 %	44 %
Materials processing and intermediate products e.g. metal and surface working, paper making, wood processing, furniture, textiles manuf., production of cycleware, dyeing/coating, food processing, etc., including related energy technology (e.g. industrial furnaces, stoves, burners), also incl. related add-on-purification technology		27 %
Final productions, end-products Buildings, vehicles, utility and consumer goods, including related energy technology (e.g. car propulsion, house heating, electr. demand of appliances), also incl. related add-on-purification technology, and producer practices		25 %
User behaviour, consumer practices		4 %
n = 288		100 %

There is, however, an important exception: long-lived complex energy apparatus such as motors in cars, jet engines, power plants, heating systems and electric appliances which consume large quantities of fuel. Food, feed and fuels have a metabolic rate of almost 100%. This makes a big difference to use-materials which by and large keep their physical structure when used. If there are important, unresolved environmental problems to be found in the use of final products, they indeed have in most cases to do with the fuels and the energy apparatus involved in using those products.

As regards the innovation life cycle stage of TEIs, as summarised in Table 3, 3% are just an idea on paper, 10% are in an early stage of research and laboratory demonstration, 26% in a more advanced stage of development, i.e. 36% in the development stage. 35% then are at market launch or shortly thereafter, or otherwise being introduced to regular practice. 16% are in experiencing growing adoption, though this does not always represent an impressive take-off. The remaining 10% represent mature technologies in a rather late stage of structuration and diffusion.

Table 3 TEIs according to stage of life cycle

Idea, concept on paper		3 %
Early stage of research and laboratory demonstration		10 %
Advanced stage of development		26 %
About market launch or introduction, or shortly thereafter		35 %
Experiencing growing adoption		16 %
Mature stage		10 %
	n = 289	100 %

The distribution in Table 3 was to be expected. Ideas and early experiments are normally not communicated to a broader public, just as technologies in a late stage of their life cycle are normally not subject to public attention since nothing particular is occurring any more. It is nonetheless important to have this documented empirically, because it confirms one of the basic recommendations that can be drawn from life cycle analysis: true progress which includes structural change, particularly regarding a change in the ecological consistency of the industrial metabolism, requires a change in path; i.e. it requires the development and implementation of new technologies rather than the modification of mature systems already in place.

It is important here to understand that with technologies, as with living organisms, the key features of a novel thing and its life course are determined upstream rather than downstream, i.e. with regard to an organism, in its genetic code and in its early days of growth, experiencing and learning; and similarly with regard to technologies, in their conceptualisation and design, in the early stages of research and development, i.e. the early stages of structuration and diffusion. What remains to be determined during later stages, consists of incremental changes and modifications of minor importance, after the point of inflection of a learning curve has been passed. Most of the environmental pressure which is caused by producing and using a certain kind of product or technology is determined right at the beginning with the conceptualisation and design of that product or technology. Once in place, there is not much left which one can do about it, aside from some improvements in later new-generation variants of that product, some percentage points of materials and energy savings in the factory, and a few percentage points by being a good consumer.

As is shown in Table 4, most TEIs do indeed bring about change in ecological consistency. In about a quarter of the TEIs, there are significant efficiency increases without a change in metabolic properties. Typical examples of this include reuse of parts and recycling of materials, e.g. of solvents or sulphuric acid, or increased fuel-efficiency in internal-combustion engines. Three quarters, however, involve some consistency change.

The biggest share, at 41%, is that of examples where there are both consistency improvements and efficiency increases, e.g. latest-generation solar cells, fuel cells of any kind, and many biotech applications of where there is simultaneously less or no environmental pressure and higher yield. The percentage of such double-surplus-TEIs is nevertheless lower than was hypothetically supposed, whereas the number of cases in which there is less inconsistency rather than really benign improvements are more than was expected.

Table 4 TEIs according to ecological consistency and efficiency

Consistency improvement without efficiency change, or efficiency unclear, or even slightly decreased		16 %
Consistency change in the sense of lesser degree of inconsistency without efficiency change, or efficiency unclear, or even slightly decreased		8 %
Consistency change in the sense of lesser degree of inconsistency combined with increase in efficiency		12 %
Both consistency improvement and efficiency increase		41 %
Mere efficiency increase without actual change in ecological consistency		23 %
	n = 281	100 %

Typical examples of lesser degree of inconsistency without efficiency change include exhaust catalysts, transmutation of nuclear waste, GM crops tolerant of agrochemicals, or HCFC-22 (chlorodifluoromethane) as a halocarbon replacements for conventional CFCs.
Replacement with SF_6 then is an example of lesser degree of inconsistency combined with some efficiency increase, because on eco-balance SF_6 helps to save CO_2 emissions. Further examples in this category tend to be incremental process innovations which help to reduce hazardous auxiliaries or materials-content while simultaneously increasing output.
An example of benign consistency improvements without efficiency changes are hydrogen-fuelled internal-combustion engines. Previous generations of solar cells and wind power, though clearly clean and metabolically consistent, even came with less efficiency than conventional like technologies.

5. Conclusions: Paradigm shift from downstream to upstream the product chain and technology life cycles

The central message from the above findings concerns a paradigm shift from downstream to upstream in the vertical product chain and in technology life cycles. I would like to mention four aspects of such an upstreaming of environmental action and policies.

First, if environmentally significant technological innovations are to be found chain-upwards rather than chain-downwards, then priorities would need to be refocused onto those industrial operations where large environmental impact actually occurs – in energy, raw materials, agriculture, chemistry and base industries, partly also in building and vehicles.

Second, the key actor groups that have to be mobilised are technology developers, product designers and producers rather than users and consumers. With a focus on products and production, one would not be spending too much time with user behaviour and consumer demand.

New technologies do not occur by way of demand pull. Important environmental innovations originate on the supply side. They are science-driven and technology-pushed, induced by ideas and interests, one of which may be solving environmental problems – though further selective impulses from the side of regulation, government and user demand certainly come in later on.

The fact that most environmental impacts are determined and caused upstream in the life cycle and upstream in the product chain puts final consumption in a somewhat paradoxical role. This ecological paradox of consumption is as follows: On the one hand, expectations of high and still rising levels of affluence are indeed among the main driving forces behind the ongoing growth of industrial production and the large volumes of turnover of the industrial metabolism; on the other hand, however, the immediate contribution of consumer behaviour to the industrial metabolism is rather low, about 5–15% to gauge it generously. This is because most of the environmental pressure, the big ecological footprints or materials rucksacks of consumer society, occur during the different steps upstream in the product chain, and are determined by the basic principles of a technology and the physical design of a product, in the early stages of their life cycle. In contrast, consumption in service businesses and private households entails final steps downstream in the product chain. Approaches such as ‘sustainable consumption’ or ‘sustainable household’ can, in the end indeed, not be particularly effective in changing the industrial metabolism.

Third, in upstreaming environmental activities, chain management by key manufacturers and trade businesses has a particular role to play. It is the manufacturers of complex end-products such as buildings, vehicles, appliances, and also large retailers such as mail order firms, who are in the position to effectively implement supply chain management. This is none of a user’s nor of a government’s business.

Final demand may be decisive with regard to the diffusion of innovations. Demand itself, however, cannot innovate, it cannot ‘buy into existence’ things which do not exist, i.e. things which are not on the market yet – with one exception, which is the demand by key manufacturers and large trade businesses, because they have, or can have if they wish so, a decisive influence on suppliers along the product chain, and a defining influence on the design and redesign of products.

Fourth, as far as government is concerned, upstreaming environmental policy would induce a shift of emphasis from regulation to innovation. Environmental policy, much more than has hitherto been the case, would have to become a policy of technology development, or will have to cooperate systematically with technological R&D policy. In consequence there would have to be a shift in the pattern of environmental policy from bureaucratic procedural control to co-ordination of national innovation networks, European at the EU level, including suitable and well balanced financial support by granting regular research funds and seed money, as well as providing venture capital and introductory aids in appropriate ways. What has to stay, though, is to set strict environmental performance standards (Ashford 1985, Kemp 1997 pp.317, Hemmelskamp/Rennings/Leone 2000). This remains by far the most effective controls instrument for environment and innovation alike (which is not astonishing given the fact that environmental standards are, or immediately translate into, technical standards).

In face of the discussed findings on TEIs one could go as far as to say: environmental awareness and will-building, regulation by law and environmental authorities, green marketing, and even green business management remain ultimately pointless in the absence of a prior strategy of technological environmental *upstream* innovation to give a common focus to environmental policies.

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