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Veröffentlichungsversion / Published Version
Arbeitspapier / working paper

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SSG Sozialwissenschaften, USB Köln

Empfohlene Zitierung / Suggested Citation:
Huber, J. (2008). *Technological Environmental Innovations (TEIs) in a chain-analytical and life-cycle-analytical perspective.*. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-121567

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Technological Environmental Innovations (TEIs) in a Chain-Analytical and Life-Cycle-Analytical Perspective

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Forthcoming in *Journal of Cleaner Production*, accepted for publication 28 Jan 2008

Abstract

This paper is based on an empirical survey of technological environmental innovations (TEIs), i.e. new products, processes and practices that come with benign environmental effects. The survey is based on product chain analysis and innovation life cycle analysis. It turns out that most TEIs occur upstream rather than downstream, i.e. chain-upwards in the beginning rather than in the end of product chains, and in early stages of technology or product development rather than in later, more mature stages. There are conclusions to be drawn for 'upstreaming' environmental activities and for focusing environmental policy upon innovation.

Technological Environmental Innovations (TEIs) and Metabolic Consistency

This paper reports on the main findings from an explorative databank of technological environmental innovations (TEIs), i.e. technical innovations that have some specific environmental advantage compared to previous like-technologies. Environmental innovation includes any kind of innovations – technical, economic, legal, institutional, organisational, behavioural – that relieve strain on environmentally sensitive resources and sinks [1]. Technology is seen here as a body of knowledge, especially know-how, but also including some theoretical know-why as well as know-what-for [2]. 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, a technological innovation had to meet the characteristics of one or several of the following environmental innovation strategies:

- Sustainable resource management
- Cleaner technologies

- Benign substitution of hazardous substances
- Bionics, biomimicry
- Design for environment; product stewardship; extended producer responsibility
- Circulatory economy; industrial symbiosis; zero-emission processes
- Add-on purification technology in emissions control and waste processing.

Another 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 metabolic consistency. These terms are closely linked to the sustainability discourse and the concept of industrial metabolism or society's metabolism [3]. Criticism of the shortcomings of the previous sustainability discourse has been a key element in the more recent discourse on ecological modernisation with its emphasis on innovation [4]. Within this context it was the starting point of the concept of ecological or metabolic consistency [5], sometimes also referred to as eco-effectiveness [6]. Whether the concept of industrial ecology would have to be included here in the same way remains to be seen, since there are quite diverging views of what industrial ecology is meant to be, e.g. rather narrow views just looking into a few aspects, preferably recycling, in the energy and manufacturing sector, as well as there are wider, more encompassing understandings fitting in with the notion of society's metabolism [7].

Metabolic consistency focuses on the structural, qualitative side of technology, not just input-output-quantities within given structures. Metabolic 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 properties 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 entrepreneurial spirit.

In terms of various lines of the 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 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.

The main purpose of this study was in fact to provide empirical evidence of the *technological* feasibility of a programme of ecological modernisation, or to put it in terms of the sustainability discourse, a programme of sustainable development which gives priority to the approaches of metabolic consistency (eco-effectiveness) and eco-efficiency rather than to an austerity programme of consumptive sufficiency. In this sense, a driving motive behind this survey of TEIs was to demonstrate the plausibility of the assumption, that ongoing modernisation of society now also includes ecological modernisation, in that new technologies and operative infrastructures of modern society tend to satisfy criteria of environmental sustainability ever more.

Collection of TEIs and database

The collection of TEIs has been carried out in connection with the Key Environmental Innovations group of the German Federal Research Ministry's Initiative on Sustainability and Innovation from 2000–2004. A databank has been created numbering 305 datasets on TEIs [8]. The databank has been fed by a continuous survey of innovations as they were reported in articles from a sample corpus containing a number of specialised journals and newsletters such as The MIT Technology Review, The Economist and The Economist Quarterly, or VDI Nachrichten (official weekly of engineers). The methodological approach thus consisted in defining a corpus of text sources with all source texts in it to be analysed and evaluated. Given its size and content, the databank is explorative rather than fully representative, though it cannot be denied to be representative to a certain degree since the text sources can claim a regular coverage of important developments in eco-innovation and 305 datasets should be a sufficient number for revealing basic profiles and tendencies of TEIs.

The source texts (articles) were checked for data and information on variables derived from the theoretical models of technology life cycle analysis and product chain analysis [9]. So 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 arguably be expected.

Some examples and trends of TEIs

The following list is taken as a compilation, partly as a selective summary from the databank, and is illustrative of examples and trends of TEIs, typically in an earlier stage of development, or about market introduction, or shortly thereafter. Although their future success cannot be taken for granted in each case, 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:

- Clean-burn technologies (e.g. flameless oxidation) in furnaces, motors and burners on the basis of fossil fuels, synfuels and biofuels
- Replacement of carbon-containing fuels with 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 stationary and mobile applications, from power stations to vehicle propulsion
- Clean coal, notably in zero-emission central power plants on the technological basis of IGCC (integrated gasifier combined cycle) and CCS (carbon capture and storage). 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 and 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 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, 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, biotechnology which makes use of transgenic organisms.

Since biotechnology is a sensitive issue, it may deserve a brief comment. Transgenic biotechnology in chemistry, materials, waste and sewage processing, and mining and agriculture 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, and to orient and shape the development of the new technology in desirable ways. Biotechnology can have considerable advantages regarding eco-efficiency and metabolic consistency, but at the same time there are new environment-health-and-safety problems which also have to be dealt with.

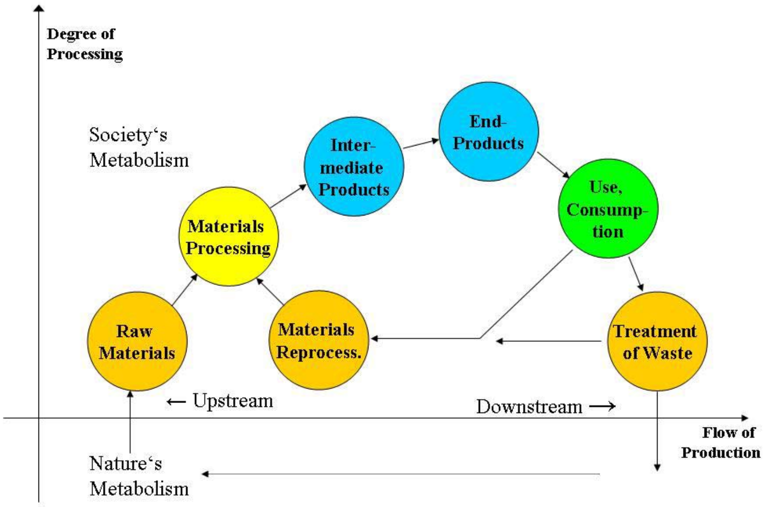
TEIs tend to be upstream the product chain and upstream a technology's life cycle

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 product chain, and upstream in the learning curve of 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.

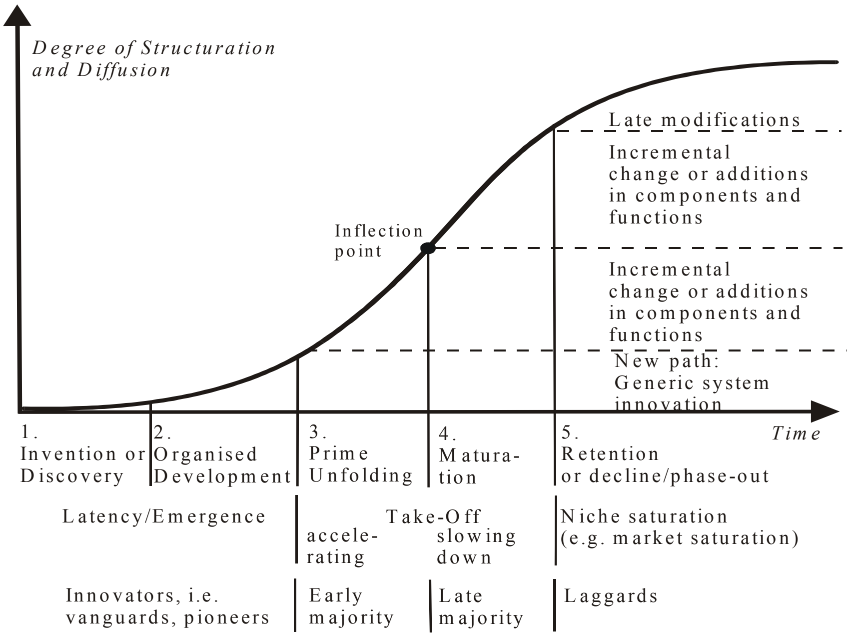
In the environmental literature, the term 'life cycle analysis' is often used interchangeably with 'product chain analysis' or 'eco-balances' that try to gauge the environmental impact of a product from first input by extraction of raw materials to last output by being definitely phased out as waste.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

Figure 1 The product chain or supply chain



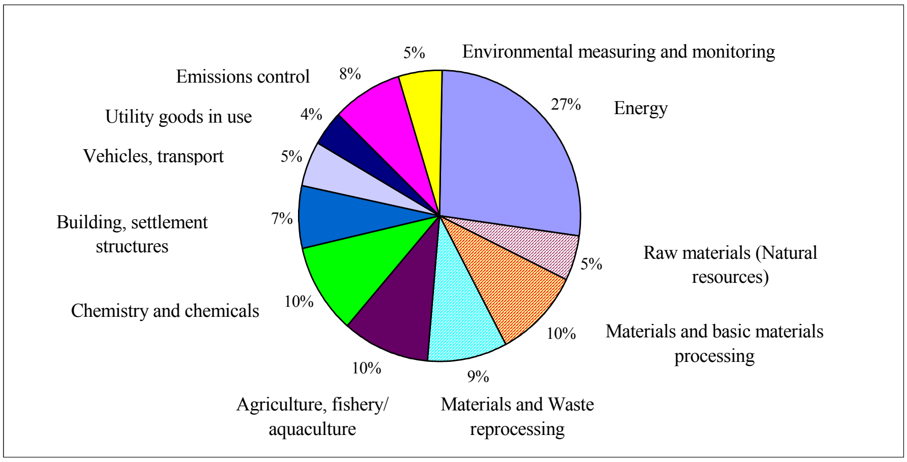
By contrast, another meaning of life cycle analysis refers to an innovation life cycle or technology life cycle as shown in Figure 2, i.e. the evolutive existence of a technology or product species.

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. 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 of the chemical industry, 52% if emissions control is added to this.

Figure 3 TEIs according to realm of innovation



We can try to specifically ascribe energy technologies and emissions control to the sectors where they actually occur within the vertical supply 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 behaviour or consumer practices from producer practices. 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 1 (n=298).

Table 1 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, aluminium, 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 manufacturing, 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, electricity demand of appliances), also incl. related add-on-purification technology, and producer practices		25 %
User behaviour, consumer practices		4 %
n = 288		100 %

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 one had to concede a possible bias in the sample and the figure on consumer goods and practices were doubled or tripled, the finding and its message would basically remain the same: TEIs are upstream rather than downstream in the vertical supply chain.

As regards the innovation life cycle stage of TEIs, as summarised in Table 2, 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 2 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 2 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 eco-quality 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 are determined in the beginning rather than in the end of its life course, 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. 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 some additional percentage points by being an environmentally aware consumer.

As is shown in Table 3, most TEIs do indeed bring about change in metabolic 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 positive change in metabolic consistency.

Table 3 TEIs according to metabolic consistency (eco-effectiveness) and eco-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 metabolic consistency		23 %
	n = 281	100 %

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 improvement is higher than was expected.

Typical examples of lesser degree of inconsistency without efficiency change include exhaust catalysts, transmutation of nuclear waste, GM crops tolerant of agrichemicals, or HCFC-22 (chlorodifluoromethane) as a halocarbon replacement 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 improvement without efficiency change 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.

Conclusions: Shift in emphasis from downstream to upstream the product chain and technology life cycles

This investigation into TEIs represents an explorative endeavour. Interpretations should thus not be overstretched. Nonetheless, there are some preliminary conclusions suggesting themselves from an angle of chain analysis and technology life cycle analysis. These conclusions are meant to be working hypotheses for further research, or as viewpoints subject to further debate. One such conclusion from the above findings would be to shift attention 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 analyses and policies.

First, if environmentally significant technological innovations are to be found chain-upwards rather than chain-downwards, then priorities would need to be focused onto those industrial operations where large environmental impact actually occurs – in energy, raw materials, metallurgy, agriculture, chemistry, as well as in building and vehicles. Of course, from the fact that most and the most important TEIs in the databank are to be found upstream rather than downstream one cannot strictly conclude that the biggest environmental impacts occur upstream rather than downstream, and that environmental policies have accordingly to concentrate on upstream supply approaches rather than downstream demand approaches. The TEI entries into the databank can indeed just be seen as pieces of circumstantial evidence rather than immediate proof; but evidence they represent. There is no smoke without fire. Environmental innovation is likely to occur where there is environmental pressure.

The empirical findings from the database correspond to a rule of thumb from the analysis of material and energy flows (MEFA) in supply chains: the more products and production processes are placed chain-upwards, the more important the potential of their environmental impact tends to be [10]. For one thing, this derives from the fact that the big ecological rucksacks – i.e. the hidden or indirect flows of unused materials, e.g. mining waste, the 'backpack' of earth and groundwater displacement and non-natural erosion – occur in the first steps of extracting raw materials [11]. Waste and unwanted by-products and emissions are still on a large scale in the subsequent steps of materials processing, i.e. transforming the materials metabolically by physical, chemical and biological processes. Third, and at the same time, extraction and processing of materials are those steps in the chain where usually most energy is consumed; with energy still being the lead indicator of environmental impact. In contrast to these upstream steps, the downstream steps of final assembly or finishing of end-products, and final use or consumption, cause 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. There is, however, one important exception: long-lived complex energy apparatus such as motors in cars, jet engines, heating systems and electric appliances which consume large quantities of fuel or electricity. 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 end-products (beyond toxicity), they indeed have in most cases to do with the fuels and the energy apparatus involved in using those products.

A second conclusion regards the actor groups to be approached. If TEIs of structural importance occur in early rather than late stages of a technology life cycle, than the key actor groups that have to be mobilised are technology developers, product designers, producers and investors rather than users and consumers – which, by the way, is in accordance with an old insight put forward within Schumpeter's theory of innovation and structural change [12]. New technologies do not occur by way of demand pull. Important environmental innovations originate on the supply side – although user and consumer demand is in fact an important feed-back factor in the development and diffusion of TEIs [13]. Consumer demand, however, neither invents nor produces supply items; its effect is *selective*. Seen from a chain-analytical perspective, consumers are not in the position of focal actors who have effective control over the choices available to cover end-user demand.

The fact that most environmental impacts are determined and caused in early stages of a technology's life cycle and upstream in the product chain puts final consumption in a somewhat paradoxical role. This ecological paradox of consumption [14] 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 industrial society's metabolism; on the other hand, the immediate contribution of consumer behaviour to society's metabolism is rather low, about 5–15% to gauge it generously. This is because most of the environmental pressure of consumer society occurs 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 society's metabolism unless such approaches are embedded in a perspective of supply chain transformation based on TEIs.

Third, in upstreaming environmental activities, chain management by key manufacturers and trade businesses has a particular role to play [15]. Within the entire product chain or supply chain, there are focal actors who have a unique position in that they combine a high degree of supply power with an equally high degree of demand power. Typically, focal actors are energy providers, water corporations, waste handling companies, the manufacturers of complex end-products such as buildings, vehicles, office and household appliances, furniture, clothes, or large industrial users such as airlines or owners of power plants, and also large retail chains and mail order firms. They are in the position to effectively implement supply chain management.

Consumer demand may be decisive with regard to the diffusion of consumer goods. But apart from the fact that consumers hardly affect selection of capital goods, final demand cannot ‘buy into existence’ things which do not exist yet – with one exception, which is the demand by basic providers, key manufacturers and large service and 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 both capital and consumer goods.

Fourth, as far as government is concerned, upstreaming environmental policy would include, much more than has hitherto been the case, a policy of technology development. Environmental policy agencies will have to cooperate systematically with technological R&D policy, or will have to expand initiatives aimed at multilevel networks of eco-innovative R&D, 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.

Equally, upstreaming environmental policy would induce a shift in emphasis towards those types of regulation which effectively foster innovation. This is not the place to look now into the pros and cons of environmental policies and regulatory instruments, but one aspect can be pointed out: an indispensable component of any policy regime aimed at promoting TEIs is to set strict environmental performance standards, in contrast to procedural standards and best-available-technology standards [16]. Demanding performance standards remain by far the most effective regulation-pull mechanism for environment and innovation alike [17].

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