Journal of Cleaner Production 18 (2010) 552–560

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Impact caps: why population, affluence and technology strategies should be abandoned

Blake Alcott [a,b,*]

[a] Gretenweg 4, 8038 Zürich, Switzerland
[b] School of Earth and Environment, University of Leeds, UK

ARTICLE INFO

Article history:
Received 20 January 2009
Received in revised form
24 July 2009
Accepted 1 August 2009
Available online 5 August 2009

Keywords:
Energy rationing
IPAT
Rebound
Efficiency
Sufficiency
Politics

ABSTRACT

This paper classifies strategies to reduce environmental impact according to the terms of the $I = PAT$ formula. Policies limiting resource depletion and pollution (*Impact*) – by heavily taxing resources or rationing them on a country basis – are thus called 'direct' or 'left-side' strategies. Other policies to achieve the environmental goal of lowering *Impact* strive to limit *Population* and *Affluence*, or to use *Technology* to lower the ratio of resource inputs to goods-and-services outputs. Next it is shown that lowering any of these 'right-side' factors causes or at least enables the other two to rise or 'rebound'. This has two consequences: 1) Since $I = PAT$ does not express these interdependencies on the right side, it is more accurately written $I = f(P,A,T)$; and 2) Success in lowering any of the right-side factors does not necessarily lower *Impact*. Rationing or Pigouvian taxation of resources or pollution, on the other hand, *necessarily* lower impact and are therefore preferable to population, consumption and technological environmental strategies. Finally, lifestyle and technology changes towards more sufficiency and efficiency would *follow* the caps as consumers and producers work to retain the greatest amount of welfare within the limits given.

1. Epigraph

> Quantitative limits are set with reference to ecological and ethical criteria, and the price system is then allowed, by auction and exchange, to allocate depletion quotas and birth quotas efficiently. The throughput is controlled at its input (depletion) rather than at the pollution end because physical control is easier at the point of lower entropy. (Herman Daly [1, p. 20])

2. Introduction

$I = PAT$, where unwanted environmental Impact depends on Population size, Affluence (consumption of goods and services per person) and Technology, suggests a distinction between left-side and right-side strategies for reaching a sustainable economic scale. 'Strategies' are simply sets of environmental policies, and the paper assumes conventional definitions of 'natural resource', 'pollution' and 'sustainability'. The left-side term, Impact, is both natural resource depletion and biosphere pollution – a non-aggregable term covering the loss of fuels, water, soil, space, ores, fish, biodiversity, favourable climate and other ecosystem amenities, etc. In this paper Impact more restrictively means *carbon-based energy resource* depletion with ensuing emissions.

Right-side terms and strategies include:

1) Population; policies achieving a lower number, *ceteris paribus*, could lower Impact.
2) Affluence (a ratio) is consumption of goods and services – desired *output* – per person; *ceteris paribus*, lowering affluence either voluntarily in the sense of sufficiency, frugality or 'living lightly', or through legal restrictions on what can enter the market, could lower total Impact computed as $P \times A$.
3) Technology is an admittedly ornery term covering *how* an economy produces and consumes: with what legal rules, type of organisation, chemicals and output–input efficiency. Consistent with the definition of Impact above, this paper singles out efficiency (another ratio) in using carbon-based energy resources as the T term; accordingly, *ceteris paribus*, policies achieving lower energy input *per unit* of output (goods and services) could lower Impact defined as the amount of energy inputs used up. Lower T means lower (energy) *intensity*, i.e. higher efficiency.

Consumer efficiency is another right-side strategy proposed within the current discussion of 'sustainable consumption'.[1] Taking the example of boiling water for a cup of coffee: more

* Tel.: +41 44 481 27 36.
E-mail address: blakeley@bluewin.ch

[1] While policy interventions in this area are loosely subsumed under the concept of 'sustainable consumption', there is in this research field no consensus on definitions and taxonomy. See [2, p. 1029–1032].

0959-6526/$ – see front matter
doi:10.1016/j.jclepro.2009.08.001

energy-efficient kettles is physical (as opposed to institutional) technological change (*T*); doing without the odd cup of coffee, for environmental reasons, is living more 'sufficiently' (*A*); boiling *no more than* the amount of water needed for the cup of coffee, in contrast, is consumer efficiency, here also classed under *T*.[2] This paper places environmental restoration activities or traditional 'end-of-pipe' measures (for example carbon capture and storage) outside the $I = PAT$ framework because their pollution reduction is at the cost of some energy depletion.

Other strategies prominent in the sustainability discussion are here taxed as 'left-side' because they directly lower Impact with no reference to population, affluence and technology, namely:

1) Reduction of carbon-based energy resource *production*, i.e. a physically defined cap on harvesting and mining; from this 'upstream' measure are then deduced rations per country.
2) Limiting energy *consumption* per person (quotas, rations); one example of this 'downstream' measure is personal carbon budgets.
3) Reduction of *emissions* – targeting pollution rather than depletion – through physically defined caps; one example is the 'Kyoto' approach with derived country caps.
4) *Taxes* on depletion or emissions high enough to limit consumption of energy inputs to the level perceived to be sustainable (Pigouvian taxes).

These sets of policies do not attempt to influence number of people, number of goods and services per person or efficiency, but instead say: "These are the maximum allowed amounts. Each country, firm and person must find the combination of reductions in population, affluence and energy intensity that most suits them."

Section 1 describes the three right-side strategies intended to indirectly lower Impact, identifies their interdependencies (how each 'rebounds') and shows that they are 1) not *necessarily* effective and 2) taken all together, costly. Section 2 more fully describes left-side strategies directly lowering depletion and pollution through legal rules of resource use, whether through physically defined *caps* or taxes raising resource *prices*; these are *necessarily* effective and require only one policy. Section 3 shows this taxonomy's relation to well-known literature and applies it to a typical impact-reduction model containing both technical and lifestyle changes. Section 4 discusses policy simplicity and political acceptability.

3. Section 1: right-side environmental strategies

$I = PAT$ was introduced with policy in mind. As Faye Duchin writes,

> Ehrlich and Holdren (1974) identified the main factors responsible for environmental degradation as population increase, affluence, and technology, providing three potentially important 'handles' for operationalizing the concept of sustainable development. [3, p. 51]; [also 4] I have called each "handle" a 'strategy'[3]

IPAT is sometimes incorrectly called an "identity". As one of its first applications shows, it is however a *formula* with which to compute the amount of Impact, namely the amount of automotive lead in the air. Paul Ehrlich et al. set all IPAT values at 1 for 1946 then compared 1946 data with that of 1968 on population, number of driven auto kilometres per person and the amount of lead emitted per driven kilometre; impact increased 414% – i.e. a *worsening* from the environmental point of view [6, p. 206, 214]. The reason the formula is thus not an identity is that both the number of driven kilometres and technical efficiency increase or decrease exogenously to the model, whereby *T* is defined *per unit* of good or service and *A* as *total units* of goods and services. In general total units consumed does *not* stay constant after efficiency increases, but rather increases, constituting 'rebound' consumption of the newly more efficiently-used input. As illustrated by Fig. 1 [7], this partly or entirely wipes out the theoretical 'engineering' savings that would materialize had number of consumed units stayed the same.

This section argues that since each right-side strategy by itself is followed by rebounds, i.e. environmentally worsening of the other two factors, reduced Impact does not *necessarily* result. Given *any* latent demand for more goods and services, and/or greater population, it is thus *certain* that no right-side set of measures is *sufficient* for lowering Impact. Therefore either additional, complementary right-side measures are required, or resort must be taken to left-side measures. Equally certainly, the difficulties of enacting, enforcing and co-ordinating many simultaneous right-side measures lowers their *cost*-effectiveness.[4]

First, before showing seven interdependencies among the three right-side factors, some general observations on rebound (illustrated intuitively by Fig. 2). The literature is decisive that rebound itself is proven,[5] and a consensus has even emerged that rebounds are 'significant' or 'relevant' to environmental policy [19]. That is, these rebounds or system adjustments – more people, more goods and services, less efficient or more 'luxurious' technology – mean that environmental improvements on the right side *cannot* translate one-to-one into lower Impact: *some* potential input savings will be consumed.

What if *all of* the potential population, sufficiency or efficiency induced savings are consumed? In that case right-side strategies would, even if cleverly and simultaneously co-ordinated, have *no effect* on Impact. A third possibility is that efficiency policies would even environmentally 'backfire', the greater efficiency causing *more* energy to be consumed than if technology had stayed the same – a thesis known as Jevons Paradox [8,17,19] or the Khazzoom–Brookes Postulate [11,12], arguing that efficiency enables new products, fuels economic growth and thus increases Impact.

While assuming, to be sure, that rebounds are large or significant (say 50% worldwide and longer-run [20]), this paper is explicitly conceptual rather than empirical. It attempts only 1) to identify and classify the various types of rebound, or right-side interdependencies, and 2) show the major consequence for environmental policy *if* rebounds are 50 or 100% – namely, that right-side changes, while certainly fruitful in securing higher material living standards and, for some societies, energy independence, are either weak or futile in achieving the depletion and pollution reductions necessary for environmental sustainability.

The general interdependencies between the *P*, *A* and *T* factors are:

P) Lower population means lower impact *only if* affluence and factor productivity are held constant;

[2] Another example of consumer efficiency is carpooling, as opposed to more efficient cars (*T*) and cycling or staying at home (*A*).

[3] Waggoner & Ausubel [5] offer a less parsimonious ImPACT identity whose C, C_2, T and T_2 are the T of this paper and which offer four 'sustainability levers' for actors to behave more efficiently and sufficiently.

[4] Working Group III's Summary for Policy Makers (IPCC Fourth Assessment Report) lists no fewer than 25 right-side measures covering energy supply, transport, buildings, industry, agriculture, forestry and waste management, policies that would be rendered *superfluous* were caps in place.

[5] See Fig. 1 and references [7–18].

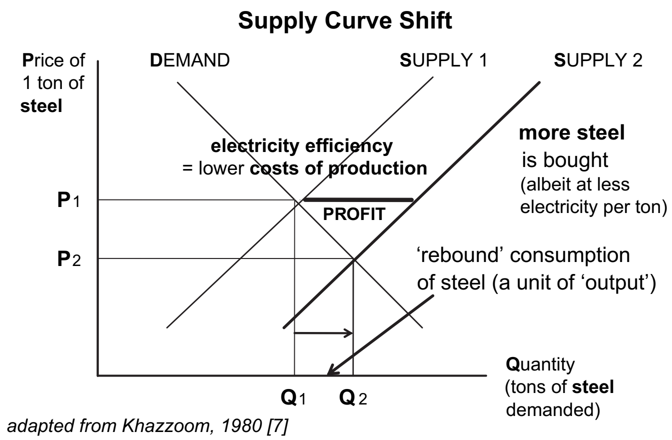

Fig. 1. Khazzoom's proof of rebound: Prices do not stay the same! Lower input use per unit of output means lower production costs, enabling suppliers to offer the same amount at a lower price or more at the same price: the supply curve shifts outward. For any demand curve sloping as depicted, i.e. with any positive price elasticity of demand, the lower price raises the quantity of good or service sold to a level above that previous to the production-cost-reducing technological efficiency increase. This 'rebound' consumption *of goods or services* entails 'rebound' consumption of *inputs* (e.g. energy) above the level it would have been had number of units consumed remained constant.

A) Only if population and efficiency are held constant does voluntary frugality lower impact;
and *T)* using resources more efficiently lowers impact *only if A* and *P* remain constant.

Put differently, impact is lowered only if there is complete 'demographic transition', full consumer satiation, and no decrease of technological efficiency[18, p. 884].

Hopefully, the following seven interdependencies establish the *plausibility* of system adjustments in any open economy.

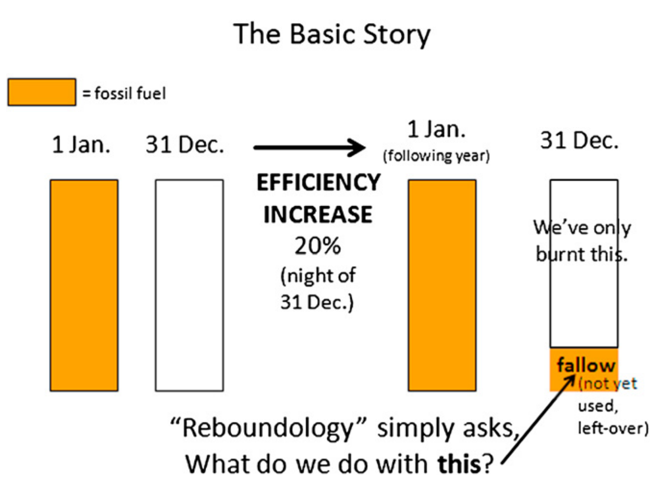

Fig. 2. Rebound visualized. During the post-efficiency-increase time period ("following year") an amount of energy equal to 20% of the previous time period's consumption is 'saved'. If the number of people and their consumption of goods and services stays the same (the *ceteris paribus* condition), the rate of consumption of energy inputs remains at 80% of the previous level and theoretical savings become real. If however population and/or affluence increase, the rate of consumption rises again – probably to the same level as before the efficiency increase. Society is free to use up the freed-up energy resources or not. The disciplines of history, economics, psychology, anthropology and political science must combine their efforts with a portion of wisdom to judge what society does.

3.1. Population change

3.1.1. *A = f(P): per capita consumption as a function of total population ('more mouths to feed')*

For all natural resources, lower *P* enables higher *A* through re-employment of the temporarily freed resources. If gross world product (GWP) is like a cake, lower population *enables* each person to consume a somewhat larger piece. Of course to the extent that cakes are products of labour, lower population can mean fewer work-hours and a smaller cake – but we are computing not total cake but cake per person. Higher population inversely means that area and natural resources per capita fall. Impact can remain unchanged [21].

3.1.2. *T = f(P): technology as a function of population size (diminishing returns)*

To the extent that lower population lessens demand for natural resources it reduces the pressure to use them more efficiently. Higher population density, inversely, is in itself an incentive to produce more efficiently due both to increasing perception of depletion/pollution and to diminishing economic returns from 'land' (soils, minerals, fuels). For instance coal and oil largely replaced wood, as did synthetic fibres much wool and cotton, and incentives are strong to more efficiently process lower-grade ores, oil sands, and soils [22].

3.2. Affluence change

3.2.1. *P = f(A): population size as a function of per capita consumption*

At lower incomes higher affluence enables survival and often higher population, while at the same time the higher levels of education and women's rights often accompanying greater affluence can lead to smaller families. At higher incomes birth rates drop – but so do death rates [23,24]. Whether overall the sign between *P* and *A* is negative or positive remains contested, meaning that policy interventions are uncertain.

3.2.2. *T = f(A): technology as a function of per capita consumption (hybrid cars, combined heat and power, lasers)*

Tracing influences on technology of the knowledge gains that accompany per capita *wealth* is a tall order. While a wealthy economy can afford to use resources less efficiently, it can also afford to invest more inefficient, cost-cutting technology (in the interest of even higher affluence). The capital junking accompanying technological innovations lowers efficiency, yet wealth enables research and development for lower energy intensity, whether to cut costs or alleviate local environmental impacts. Here, too, the overall sign of the relationship is debatable.

3.2.3. *$A[\varepsilon P_x] = f(A[\varepsilon P_y])$: the affluence of one subset [ε] of the population as a function of (changes in) the affluence of another subset*

Given limited amounts of labour and natural resources, a unit of consumption by anyone with ability to pay excludes others from that consumption. Relevant to environmental strategies is the fact that if someone for environmental reasons voluntarily lowers his or her affluence, the system-wide result can compensate for this. Fig. 3 shows how the frugality initially lowers energy demand, a demand-function shift meaning lower energy *prices*; this in turn enables marginal consumers to increase their demand, eliminating some or all of the initial, frugality-induced resource saving. This 'sufficiency rebound' means that a net decrease of Impact does not necessarily follow from voluntary frugality [25]. Although the size of this global rebound is even less satisfactorily measured than the efficiency rebound, both

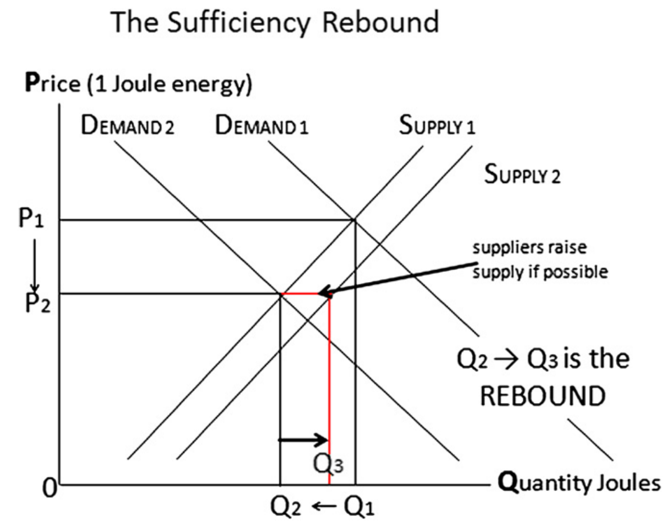

Fig. 3. Rebound after voluntary frugality. Doing without goods and services – either voluntarily or in compliance with political decisions – lowers quantities consumed by assumption, and constitutes a leftward shift of the demand curve. The resulting lower prices attract other consumers who are *not* behaving 'sufficiently' in the interests of the environment. This reaction raises quantities demanded above the level after the 'sufficiency shock'. If suppliers can raise production at the new price level the process is complete, and some rebound assures that for the whole system, voluntary frugality does not result one-to-one in real input savings. Again, prices do not stay the same.

widespread poverty and material aspirations of the well-to-do suggest that all freed resources would likely be snapped up.

3.3. Technology change

3.3.1. $P = f(T)$: population size as a function of technology (green revolution)

Increases for instance in agricultural efficiency have usually caused population increase, with various effects on affluence but likely leaving Impact the same. Increased yield per hectare has never meant that we take land out of production. This rebound effect, which renders *P* partly *endogenous* in energy-consumption models, has been largely neglected [26].

3.3.2. $A = f(T)$: affluence as a function of technological (fuel-) efficiency (efficient equipment)

Were the right side of $I = PAT$ multiplicative (no interdependencies), lower *T* (higher efficiency) would automatically lower *I*. But higher efficiency – either technological or organizational – raises income, consumption, or wealth ($P \times A$). This uncontested rebound means Impact cannot be thereby reduced to the full extent of potential savings, computation of which multiplies energy input per unit of goods-and-services by goods-and-services outputs while holding the *number of output-units constant*. Unfortunately, thirty years after Khazzoom's proof of this, this naïve, non-economic view dominates not only political programmes,[6] but most academic literature researching cleaner production, efficiency standards, barriers to cleaner technology, renewable energy, agricultural productivity, etc.

To my knowledge only the UK government is beginning to acknowledge rebound, in some sectors, when evaluating its energy-efficiency programmes. Otherwise, as a representative of the Swiss Energy Office recently said to me, "Until we know exactly how big rebound is, we treat it as zero" [27]. The jury to be sure is still out on the precise relationship between per-unit efficiency changes, per unit price changes and total units consumed; in fancy terms, the efficiency elasticity of demand has not been micro-economically computed [15]. Ignoring rebound altogether, however, is scientifically inacceptable, analogous to postponing acknowledgement of climate change until scientists unequivocally prove that human activity will raise average temperatures by 2.78 degrees by June 2041.

For even a rudimentary case that rebound equals unity much additional space would be needed. Briefly, nevertheless, note only that there are at least five lines of argumentation that the energy resources temporarily freed by efficiency increases are fully used up by world economic activity:

1. Time series show high correlation between increased production efficiency – mainly business-as-usual attempts to save costs, lower prices and increase sales – and increased energy consumption [17,28,29,30, p. 243, 338] and [31]. Of course correlation is not causality, yet the empirical data seems strong enough to shift the burden of proof onto the position that rebound is less than 100%.
2. A factor of production that becomes more productive thereby enjoys, within substitutability constraints, higher demand compared to other factors of production [9,11,15].
3. Two roles of energy efficiency increases are to date not well-investigated: a) enabling *new uses* for energy and b) saving *time* that is used for further production and consumption; these would have to be booked under rebound [8,19,32].[7]
4. Popular models yielding relatively low rebound are methodologically weak: often only direct rather than *total* rebound is measured[8]; population and GDP are fully exogenous; marginal consumption is assumed to be less energy-'intensive'; monetary metrics neglect that 'income effects' for the consumer are counterbalanced by the necessarily *lowered* income of energy sellers [34].
5. *Labour* input efficiency has risen constantly with economies of scale, stable legal systems, trade, factory-floor re-organisation, faster communication, transport infrastructure, etc. – yet no one maintains that thereby *less* labour employment has been the result [17].

Current evidence is thus such that the *burden of proof* can just as well rest on showing what has never been demonstrated: that per-unit input savings cause overall savings (i.e. rebound <100).

For clarity: high-rebound theory does not claim that energy efficiency increase is the *only* cause of greater energy consumption; labour efficiency increase, new energy sources, some exogenous population increase or rising energy return on energy investment (EROI) do their part. Note as well that an exogenous, increased supply of energy from 'renewable' sources also rebounds, namely in a way similar to the sufficiency rebound: lower prices of non-renewables enable marginal consumers to increase their demand. Thus at least in the longer run consumption of *both* types of energy could continue to increase.

[6] In the past few weeks alone the author has collected around ten newspaper items extolling the 'holy trinity' of greater efficiency, renewables and less waste – either op-ed articles or reports of programmes by Barack Obama, Tony Blair, John Podesta, McKinsey Inc., or the Chinese and Swiss governments – all in complete ignorance of rebound.

[7] It could be that "technology is [only] a catalyst, as it were, to induce the latent ability of a resource to emerge." [33, p. 43].

[8] 'Direct' rebound follows from the increased consumption, post-efficiency-change, of exactly the good or service newly more efficiently (cheaply) produced; e.g. the owner of a more efficient car will drive more kilometres.

Efficiency has positive connotations, always having stood for cost-cutting measures that enable individual households to save, firms to increase profits, and in general greater material comfort and health – all non-environmental goals. As in Jevons' day concerning peak coal, though, efficiency has been co-opted by environmentally concerned citizens and researchers in hopes that it is a tool to delay peak oil or global warming. The existence of rebounds, however, means that policies to reduce population, affluence and energy intensity are *not sufficient* to reduce Impact. Luckily, however, this ineffectiveness need not terribly worry us, for right-side strategies are also *not necessary* to lower Impact. The next section describes several alternatives that do guarantee environmental success, all of which are 'on the policy table'.

4. Section 2: left-side environmental strategies

Since any change in a factor on $I = PAT$'s right-side thus causes changes in the other factors (*ceteris paribus* does not obtain) we should replace $I = PAT$ with $I = f(P,A,T)$, expressing these interactions as in Fig. 4. Sometimes, in fact, the literature accepts that therefore right-side measures at best weakly affect Impact, for instance when it is argued that too much effort has gone into the design and implementation of production-side efficiency measures and not enough into population reduction or into lifestyle changes in the direction of sufficiency and consumer efficiency [2,3,19,35]; focus should shift from *T* to *A* (*P* receives little attention). The conclusion drawn in this paper, however, is to shift attention to the left side of $I = f(P,A,T)$, to strategies that directly proscribe exceeding maximum depletion and pollution rates.[9]

The Swiss forest law of 1876 aimed to maintain a given stand of trees, and took the direct path to guaranteed success. Preventing diminution of the number of trees was not pursued by trying to reduce population, urging people to use less wood and convert less forest to agricultural uses, or increasing wood's efficiency in heating, building, or paper-making: it simply forbid it. Some overfishing has similarly been stopped in recent years. The 'Kyoto' plan says that no more carbon-based energy resources *may* be burned than is consistent with, say, 450 parts CO_2-eq. per million by volume in the atmosphere. One could alternatively cap global *production* of the troublesome substances oil, gas and coal. Andrew Simms for instance quotes the claim that "80 percent of the fossil carbon that ends up as man-made CO_2 in the earth's atmosphere comes from only 122 producers of carbon-based fuels", enabling at low administrative cost reductions to for instance half the 85 million barrels oil-equivalent produced now per day [36, p. 177] and [37]. As in wartime Britain, national caps can be distributed among the population in the form of rations. These policies or strategies are *sufficient* for the environmental goal, giving them *a priori* advantage over strategies whose success is impeded by compensating reactions in other parts of the economic system.

Two types of policies are now distinguished, both limiting consumption at physically defined maximum amounts: 1) *taxing* the offending substances so that their prices are high enough to prevent demand from exceeding the politically decided level; 2) *forbidding* consumption above this level. The second policy is straightforward while the first is indirect (via 'the right prices'), but both achieve the same end.

The Pigouvian taxes limit quantity consumed through the price mechanism, at given demand functions for firms, households and individuals. The taxes can fall either on these entities or, through 'excise' taxes, far 'upstream' [38–40]. Perhaps it is a problem that

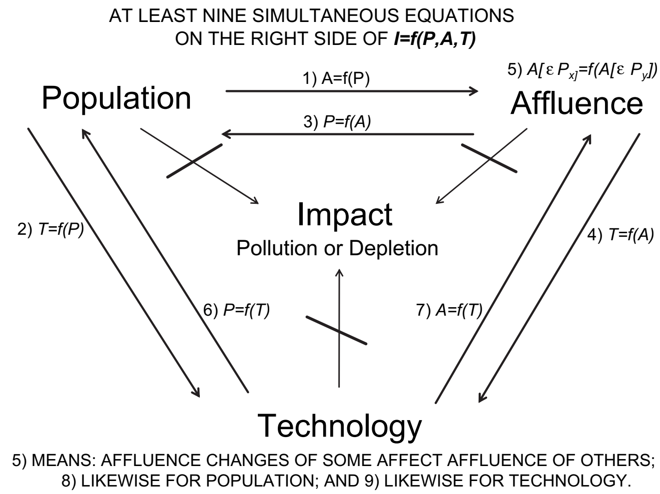

Fig. 4. Loop diagram of seven of the nine interdependencies. The arrows between the terms *P*, *A*, and *T* stand for interdependencies where the signs are usually opposites and represent rebounds. The arrows are numbered according to their appearance in the text. There is no direct or guaranteed effect on Impact of changes in the right-side terms.

the tax revenue then gets spent for, among other things, the taxed substances; yet in theory raising the tax even higher would wipe out this second-order demand or 'eco-tax rebound'.

Bypassing the tax and price system can take several forms.

1. The *production* caps already mentioned can be enforced 'upstream', as they reach the surface of the earth. These are routinely implemented by OPEC, for instance, for non-environmental reasons; groundwater regimes have capped water for the protection of aquifer levels for centuries. Such policies can be measured and enforced purely physically, as can simple *import* restrictions for countries not producing fossil fuels.
2. *Consumption* caps have a long tradition consisting of entitlements to buy or physically distributed rations. Economic analyses of 'sale if and only if coupon' abound.[10] The number of allotments and the amount of resource per allotment are of course deduced from the global maximum but enforced 'downstream' – i.e. well after the energy resource has been mined, refined and embodied in goods and services, implying the problem of measuring how much energy is embodied in a given good or service [47, p. 1073, 1079] and [35]; alternatively, only purchases of energy itself can be rationed.
3. Whereas production and consumption caps implicitly limit emissions as well, the UNFCCC strategy, for instance, aims only at lower pollution Impact, leaving aside the sustainability concerns of declining resource amounts.

Please imagine these policies as global (to avoid free-riding countries) and defined on a country rather than individual basis (to accommodate changes in population size). Current debate concerns not the environmental effectiveness of these strategies, which is given, but rather their relative economic *costs*. The three main rivals are: "domestic tradable quotas, upstream auction or a carbon tax with lump sum recycling." [40, p. 34] For instance taxes might be preferred over consumption quotas because a tax system is already in place, but rations without taxes could be seen as more equitable. This is not the topic of this paper, however, and one can legitimately

[9] Roughly, left-side caps and Pigouvian taxes are 'supply-side', while P, A, and T measures can be called 'demand-side' strategies.

[10] See references [41–49].

ask whether environmental policy should be concerned with economic efficiency and economic growth at all. Their main relevance to environmental goals seems to be that economically more efficient schemes are more easily politically 'sold' to firms and voters [40, p. 5, 10,11, 60,61]. But any left-side strategy renders superfluous a plethora of right-side measures [40, p. 20]. What is left in or on the ground is not yet consumed.

Thus, while causality does not necessarily operate from the right to the left side of IPAT, in the reverse direction it does. Real input limits must lead to large changes in population, affluence and technology since individuals, firms and political units would autonomously and de-centrally adjust their behaviour to maximize their welfare within those limits. Family size might decrease, technology would undoubtedly become more efficient, and a measure of sufficiency would become not only necessary but acceptable [47, p. 1077–79]. Right-side strategies thus actually 'put the cart before the horse', whereas left-side caps would motivate us to get as much utility as possible out of the capped amount. Efficiency, for instance, is then correctly seen as a tool, not for sustainability, but for affluence maximization.

5. Section 3: a typical policy-relevant model

Sections 1 and 2 try to show that environmental goals can be striven for directly or indirectly; that the indirect approaches on the right side of $I = f(P,A,T)$ have no necessary 'impact' on Impact; that where rebounds are at unity they leave Impact untouched; that in any case Impact falls less than the amount computed when $I = PAT$ is used as a multiplicative, static formula innocent of interdependencies; that co-ordinating right-side policies to counteract rebounds is daunting and costly; and that alternatives are available in the form of Pigouvian taxes and caps.

A critique of some well-established and well-funded strategies and research programmes is now possible, and to apply the analysis and integrate it into the more familiar discourse of technological change, cleaner production and lower 'ecological footprints', this section discusses the typical model of Duchin proposing policy "handles" explicitly based on Ehrlich's IPAT equation [3, p. 51] and [50]. In addition to the population strategy (*P*) it includes "two main avenues for bolder scenarios: technological change [*T*] and change in the lifestyles of households [*A*]." [3, p. 20; also p 51, 60] The former is largely the efficiency strategy, while the "lifestyle" category subsumes both personal and community consumption choices, e.g.

> a dramatic reduction of reliance on private automobiles, which could be made possible and desirable only through the increased availability of nonmotorized and public transport and mixed-use community design that satisfies requirements with far less personal displacement. [3, p. 71]

This category, termed "conservation" as opposed to "efficiency", also includes "practically costless improvements in 'housekeeping,' recovery of waste heat, and electronic controls for a variety of processes" as well as "process improvements [and] cogeneration". [50, p. 17, 91–96] Much of this falls under the *structural change* strategy wherein levels of utility and expenditure do not fall but are shifted to less 'environmentally intensive' goods and services [35,51].

In Duchin's structural economics model, one of the main measures "leading to a contraction of factor inputs [is] improved energy efficiency" [3, p. 55], and one such needed technological change is "more fuel-efficient cars" [p 20]. But in this and other models there is no formal integration of system-wide effects like more cars and more driven kilometres: rebound is zero. Actually, Duchin identifies macroeconomic rebound when she writes that "more extensive recycling of materials and more fuel-efficient cars" cause the economic growth necessary for development; "as population and affluence increased, pollution could also be expected to grow" [p. 19]. This indeed seems to describe backfire, i.e. an *increase* in Impact when *T*, as energy intensity, is reduced.[11]

With the analytical tool of $I = f(P,A,T)$ two further criticisms of this and similar models can be made. *First*, one can in fact accept the simple, multiplicative form of $I = PAT$ as a static *description* of an economy, showing Impact at any given time: Duchin's "structural economics… describe[s] changes in lifestyle and technology in concrete detail" [3, p. 51]. But the model is intended to be policy-relevant: "[A]n explicit focus on households [should not be] absent from work about the restructuring of economies in response to environmental pressures"; "importance for policy" is generally claimed [3, p. xiii, 60, 70]. For the step from environmental *bookkeeping* to environmental *action* to be taken, however, one needs a *dynamic* treatment describing the relations between all four terms.

Second, the efficiency and structural change claimed by the model to reduce Impact are, and can only be, expressed in *ratios*. Efficiency is an intensive variable for output/input, while structural change is to be from a more environmentally intense sector to one less so. But Impact is an *extensive* dependent variable, an absolute number, e.g. of joules or tonnes of CO_2, and thus cannot be deduced from changes in an intensive variable without multiplying by another whole number. Within IPAT, that is, the ratios *A* and *T* alone yield no information about *I* [17]. In anthropomorphic terms, the environment does not 'care about' ratios.

6. Section 4: discussion

What rationing of carbon, once enacted, might mean in terms of 'uses' of equipment emerges, for instance, from the U.K. war experience:

> Between 1938 and 1944 there was an enormous 95 percent drop in the use of motor vehicles in the UK. Even in the United States fuel was strictly and successfully rationed to eliminate unnecessary travel…. Across all goods and services consumption fell 16 percent but with much higher drops at the household level. In just six years from 1938 British homes cut their use of electrical appliances by 82 percent. [36, p. 159]

Statutory, economy-wide reductions in overall fuel consumption *preceded* adjustments in production technology and 'lifestyles'. Similarly, during the period of high fuel prices in summer 2008 news media reported a shift in the US away from heavy, fuel-inefficient cars. If, on the other hand, the reverse is assumed, and the reductions are thought to *follow from* some combination of rich-world frugality and more efficient production and consumption, any resulting expansions elsewhere in the economy stand in the way.

This simplicity of caps or Pigouvian taxation moreover enables full focus on the set goal of changing the left-side term; after all lower rates of reproduction, more frugal consumption and technological 'progress' in the form of greater efficiency are *not* the (environmental) goals. I would suggest that while the debate around 'Kyoto' is salubrious in making no bones about the radical emissions cuts required, it would be even clearer to define these

[11] This environmentally bad effect is then contradictorily laid at the door of *too little* efficiency improvement: pollution rises "not nearly as steeply as if no corrective actions had been taken." [3, p. 19]; also [52] Again, economic growth and population are fully exogenous [53], and efficiency's sign is first negative, then positive.

cuts in terms of less carbon-based *resources* consumed – assuming of course given levels of efficiency, techniques of carbon capture and storage, etc. As one economist sceptical of the environmental effectiveness of the technological 'handle' wrote,

> [i]t would be more straightforward to direct that there should be reductions in 'world economic activity', of specific emissions, or seek worldwide agreement to placing heavy taxes on the offending fuels. [9, p. 201].

Further, "adjustments of efficiency are "oblique" and we would do better to unabashedly "outlaw, ration, and tax." [10, p. 363–64]

There are perhaps three main reasons why right-side strategies are nevertheless widely preferred: 1) they are perceived as more consistent with individual freedom; 2) they are seen as less painful and therefore politically more acceptable; and 3) caps or taxes offer no escape from the harsh fact of the planet's (limited) carrying capacity.

Freedom: Right-side restrictions on biological reproduction, affluent lifestyles and technological inefficiencies can, of course, be legislated. In the real world, however, China is perhaps the only example of the first, and perhaps the Soviet Union and Cuba examples of the second. In contrast, mandatory efficiency standards in buildings and machinery, or waste-minimization, are well-known – yet often take the form of mere encouragement through subsidies, tax breaks, energy-efficiency labels and voluntary agreements. With caps and Pigouvian taxes, however, there are no voluntary agreements, just rules. The call is for mutually agreed upon mutual coercion, for politics rather than individual behaviour change, and for accepting the often-scorned but very human attitude of 'I will only if you will.' [54, p. 147–156, 227–230] and [55].

Political acceptance: Caps and taxes are indeed unpopular, partly due to this high value culturally placed on freedom. Conversely right-side measures promise not only considerable retention of such freedom but a *win-win* vision [25,49]: Doing without some consumption will not only help the environment but is good for you – e.g. bicycling and vegetarianism; or, less consumption requires less income, less work and leaves more free time. Producing more efficiently is said to double affluence at half the environmental cost [56] – a 'lunch you are paid to eat'. Is the choice then between popular, ineffective policies and unpopular, effective ones?

Within the transportation sector Susan Owens and Richard Cowell have similarly observed that because it is so difficult to reduce

> the rate of traffic growth… a view that policy should focus on reducing pollution and congestion, rather than the volume of traffic *per se,* has prevailed, conveniently shifting attention towards vehicle performance, traffic management and selected improvements in the road network. [57, p. 97]

The term 'conveniently' pinpoints the urgent problem of direct strategies: contraction and economic shrinkage ('degrowth') are taboo. The opposing discourse or rhetoric surrounding right-side measures portrays them as painless: save energy and money at the same time.[12]

Carrying capacity: What if preventing global warming is simply not possible at today's world-average level of material affluence, assuming population will grow by another two billion? What if ethical decisions to leave considerably more exhaustible resources for posterity must increase poverty today? Given that poverty persists even at present levels of groundwater use, fishing and fuel consumption, what if reducing Impact to sustainable levels raises this 'opportunity cost' (poverty today) to heights simply inconsistent with our humanism? It is very painful to realize that for the several billion poor in the world there arises a nasty trade-off between sustainability and subsistence; a professed goal of the relatively rich of material equity is put to the test.[13] Framing the environmental question in terms of amounts of resources used up allows no escape from these ethical questions.

Finally, care should be taken not to conflate different policy goals. For instance, lowering population and raising energy efficiency can indeed be said to be 'good' – good for affluence or personal material welfare, good for other species, or aesthetically good. But they are good for lowering environmental impact only indirectly: When right-side strategies demonstrate to us that 'doing without' isn't all that bad, and that technically, efficiency can be increased enough to maintain a comfortable level of consumption, we more readily vote for caps – they become politically more palatable. Similarly, lowering the affluence of the rich under certain institutional conditions raises the affluence of the poor. But this is not *environmental* policy; logically, efficiency and sufficiency contribute only to the 'development' part of sustainable development.

7. Conclusions

In terms of $I = f(P,A,T)$, this paper argues for giving preference to direct, left-side strategies over indirect right-side strategies to reduce Impact, defined as resource depletion and environmental pollution. This judgment applies two criteria: 1) likelihood of environmental effectiveness or success; and 2) simplicity or parsimony. Concerning the first, rebounds among right-side factors sever any necessary connection between right-side improvements and lower Impact, and a case can even be made that these rebounds are large enough to render them fully ineffective; the lack of measurable success of standard strategies for efficiency and structural or lifestyle change is in any case shown by Fig. 5.

Concerning the second criterion, simplicity as invoked here has less to do with lower transaction costs (economic efficiency) than with conceptual parsimony, ease of policy design and political clarity. In Tina Fawcett's words:

> One of the key benefits of carbon rationing is that it provides a framework for carbon reductions. No longer might it be necessary to have separate government policies and programmes to promote everything from cycling strategies to efficient refrigerators. Under carbon rationing, the carbon 'market' should recognise the benefits of renewable energy, household insulation and low carbon methods of transport. [47, p. 1077; also 54, p. 34]

Instead of building codes, demand management, product labelling, work pattern change, urban design, food miles, individual ecological footprints, progressive electricity tariffs and exhortations to leave one's wedding in a rickshaw, we would have one overall tool.

In summary and conclusion:

1. Policies or strategies are usefully classified under the four terms of $I = f(P,A,T)$. They either lower Impact directly, or attempt to lower it by lowering population, affluence (consumption of goods and services per person) or the energy intensity of producing goods and services.

[12] Caps are considered politically odious, but so are income tax, parking restrictions and military service, which we accept.

[13] Even the environmentally and ethically sound strategy of contraction and convergence (like the UNFCCC's 'common but differentiated responsibility') must leave open the carrying-capacity question of what the *ecologically* dictated level of throughput, for a given population, would mean for poverty.

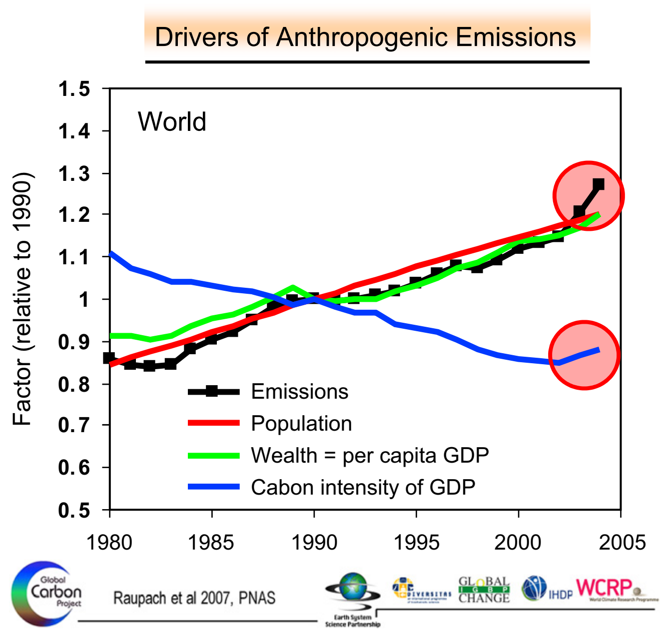

Fig. 5. Energy efficiency and energy consumption rise in lock step. The downward-sloping line is carbon (for this paper, energy) *intensity*, merely the inverse of carbon (energy) *efficiency*. The efficiency line is roughly the same as the depicted upward-sloping lines, of which emissions pertain directly to this paper. Efficiency and emissions are almost perfectly correlated. Contrary to standard interpretations, where emissions rise *in spite of* efficiency rise, high-rebound theory says that efficiency rises *enable* the emissions rises. In any case, these hard facts should give standard theory pause.

2. Right-side policies are numerous, and moreover must be co-ordinated in order to change Impact; in contrast, left-side policies (capping inputs or taxing them heavily) are single and simple.
3. The interdependencies between right-side measures are *rebounds*: reductions in one factor can result in compensatory increases in others, perhaps leaving Impact even untouched; left-side policies cannot, by definition, rebound.
4. Even when the rebounds are 'low' – say, between 30 and 50% – they do not reduce Impact in the one-for-one way that multiplication of the three right-side factors would indicate; left-side policies, on the other hand, need not be measured.
5. As right-side measures become more numerous, and/or require more co-ordination, or as rebounds approach 100%, they become less *cost*-effective compared with left-side policies.
6. If rebounds are 100%, no reduction of Impact occurs, i.e. the policies, even in combination, are *ineffective*; left-side policies, in contrast, *necessarily* achieve the environmental goal.
7. Caps and Pigouvian taxes are therefore superior to right-side strategies in terms of effectiveness, cost-effectiveness and simplicity of design and enforcement.
8. Once energy-input limits are set, people's desire to maintain as much welfare as possible would lead to adjustments in reproductive, consumer and producer behaviour, with little or no need for policy interference.

A wide range of political parties, governments, editorials, NGOs and academics advocates something of a standard set of policies to fight global warming or reduce energy consumption in the interests of sustainability or energy independence: energy efficiency, voluntary frugality, renewable energy, structural change, waste reduction, clean production, recycling and consumer efficiency. This paper has sketched and classified theoretical reasons why these policies do not achieve their environmental purpose – whatever other virtues they may have. Empirically, to my knowledge, there has never been *proof* that these measures or strategies work. Indeed, in spite of efforts along the lines of these strategies, energy consumption continues to climb. The trend is not even broken. In this situation it behoves advocates of these approaches to accept a burden of proof at least as strong as that resting on the position that rebounds are 100% or more. I see no reason to prefer, or continuing pursuing, strategies that are uncertain and neither sufficient nor necessary to reach the environmental goal of depletion and pollution reduction.

Simms describes a meeting with UK government officials searching for ideas to take with them to Johannesburg in 2002. He asked

> [w]hy weren't they honest with the British public and tell them what life would be like if necessary emissions cuts were made. Why not prepare public opinion now, by admitting the scale of required action, so it would be possible to sell the appropriate policies later? There was the sound of choking. Unlike the forthrightness of public communications during the war, the most the civil servants felt able to do now was 'suggest' that people might like to make one less car journey a month. [36, p. 163]

Similarly, forbidding old-fashioned light bulbs, as foreseen by impending 'cutting-edge' Australian or Swiss law, is no more than pussyfooting around.

Some decades ago political economists such as Kenneth Boulding, Herman Daly and William Ophuls advocated rationing, but this tradition within environmental and ecological economics, while never eschewed, has fallen into neglect. Yet caps, either directly or through Pigouvian taxes, would not only enable clear discussion but guarantee policy success. Population, affluence and technological adjustments at the individual level will then help us retain considerable welfare within the decided-upon limits, even if we consciously decide to live to some degree unsustainably.

Acknowledgements

I thank the anonymous reviewers, Maurie Cohen, Marcel Hänggi, Roman Nägeli, Christer Sanne, François Schneider, Irmi Seidl, Özlem Yazlik, and the staff and institution of the Zentralbibliothek Zürich.

References

[1] Daly H. The economics of the steady state. American Economic Review 1974;64(2):15–21.
[2] Jackson T. Negotiating sustainable consumption. Energy & Environment 2004;15(6):1027–51.
[3] Duchin F. Structural economics: measuring change in technology, lifestyles, and the environment. Washington, DC: Island; 1998.
[4] Ekins P. The sustainable consumer society: a contradiction in terms? International Environmental Affairs 1991;3:243–57.
[5] Waggoner PE, Ausubel JH. A framework for sustainability science: a renovated IPAT identity. Proceedings of the National Academy of Science USA 2002;99(12):7860–5.
[6] Ehrlich PR, Ehrlich AH, Holdren JP. Human ecology: problems and solutions. San Francisco: W.H. Freeman & Co.; 1973.
[7] Khazzoom JD. Economic implications of mandated efficiency in standards for household appliances. Energy Journal 1980;1(4):21–40.
[8] Jevons WS. In: Flux AW, editor. The coal question: an inquiry concerning the progress of the nation, and the probably exhaustion of our coal-mines. 3rd ed. New York: Augustus M. Kelley; 1905. 1865, reprint 1965.
[9] Brookes L. The greenhouse effect: the fallacies in the energy efficiency solution. Energy Policy 1990;18(2):199–201.
[10] Brookes L. Energy efficiency fallacies revisited. Energy Policy 2000;28 (6/7):355–66.

[11] Saunders HD. The Khazzoom–Brookes postulate and neoclassical growth. Energy Journal 1992;13(4):131–48.
[12] Wirl F. The economics of conservation programs. Boston: Kluwer Academic; 1997.
[13] Sanne C. Dealing with environmental savings in a dynamical economy – how to stop chasing your tail in the pursuit of sustainability. Energy Policy 2000;28(6/7):487–95.
[14] Binswanger M. Technological progress and sustainable development: what about the rebound effect? Ecological Economics 2001;36(1):119–32.
[15] Sorrell S. The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. UK energy research council. Available from: www.ukerc.ac.uk/Home.aspx; October/November 2007.
[16] Herring H, Sorrell S, editors. Energy efficiency and sustainable consumption: the rebound effect. Basingstoke, UK: Palgrave; 2008.
[17] Polimeni J, Mayumi K, Giampietro M, Alcott B. The jevons paradox and the myth of resource efficiency improvements. London: Earthscan; 2008.
[18] Holm S-O, Englund G. Increased ecoefficiency and gross rebound effect: evidence from USA and six European countries 1960–2002. Ecological Economics 2009;68(3):879–87.
[19] Alcott B. Jevons' paradox. Ecological Economics 2005;54(1):9–21.
[20] Barker T. The global macroeconomic rebound effect of energy efficiency policies: an analysis 2012–2030 using E3MG. Cambridge: Cambridge Centre for Climate Change Mitigation Research. Available from: http://www.landecon.cam.ac.uk/research/eeprg/4cmr/news.htm; 2009.
[21] Bartlett A. Reflections on sustainability, population growth, and the environment. Population and Environment 1994;16(1):5–35.
[22] Barnett HJ, Morse C. Scarcity and growth: the economics of natural resource availability. Baltimore: Johns Hopkins Press; 1963.
[23] Abernethy V. Why the demographic transition got stuck. Population and Environment 1993;15:85–7.
[24] Cohen JE. How many people can the earth support? New York: Norton; 1995.
[25] Alcott B. The sufficiency strategy: would rich-world frugality lower environmental impact? Ecological Economics 2008;64(4):770–86.
[26] Giampietro M. Sustainability and technological development in agriculture. BioScience 1994;44(19):677–89.
[27] Personal communication, Feb. 2009.
[28] Cipolla C. The economic history of world population. Harmondsworth. U.K: Penguin; 1962–1966.
[29] Herring H. Energy efficiency – a critical view. Energy 2006;31:10–20.
[30] Smil V. Energy in nature and society. Cambridge, Massachusetts: MIT; 2008.
[31] GCP. Recent carbon trends and the global carbon budget, updated to 2006; drivers of anthropogenic emissions. Available from: www.globalcarbonproject.org; 2009.
[32] Rosenberg N. Exploring the black box: technology, economics, and history. Cambridge: Cambridge U. Press; 1994.
[33] Mayumi K. Temporary emancipation from land: from the industrial revolution to the present time. Ecological Economics 1991;4(1):35–56.
[34] Madlener R, Alcott B. Energy rebound and economic growth: a review of the main issues and research needs. Energy 2009;34(2):370–6.
[35] Hinterberger F, Luks F, Schmidt-Bleeck F. Material flows vs. 'natural capital': what makes an economy sustainable? Ecological Economics 1997;23(1):1–14.
[36] Simms A. Ecological debt: the health of the planet and the wealth of nations. London and Ann Arbor: Pluto; 2005.
[37] Daly H. Economics, ecology, ethics. San Francisco: WH Freeman; 1973–1980. p. 160–8.
[38] Weitzman ML. Prices vs. quantities. Review of Economic Studies 1974;41(4):555–70.
[39] Nordhaus WD. An optimal transition path for controlling greenhouse gases. Science 1992;258:1315–9.
[40] Tietenberg T. Resources for the future. Washington, D.C: Emissions Trading; 2006.
[41] Scitovsky T. The political economy of consumers' rationing. Review of Economics and Statistics 1942;24:114–24.
[42] Reddaway WB. Rationing. In: Chester DN, editor. Lessons of the British war economy. Cambridge: Cambridge U. Press; 1951.
[43] Tobin J. A survey of the theory of rationing. Econometrica 1952;20(4):521–53.
[44] Hurwicz L. The design of mechanisms for resource allocation. American Economic Review 1973;63:1–30. Papers and Proceedings.
[45] Seyfang GJ. Local exchange trading systems and sustainable development. Environments 1996;38:5–18.
[46] Eger T, Weise P. Gutscheine und zertifikate. In: Tietzel M, editor. ökonomische theorie der rationierung. München: Franz Vahlen; 1998.
[47] Fawcett T. Carbon rationing and personal energy use. Energy & Environment 2004;15(6):1067–83.
[48] Starkey R, Anderson K. Domestic tradable quotas: a policy instrument for reducing greenhouse gas emissions from energy use. Tyndall centre for climate change research. Technical Report 39, December. Available from: www.tyndall.ac.uk; 2005.
[49] Lee M. EU environmental law. Oxford: Hart; 2005. p. 3–9, 183–85, 195–204.
[50] Duchin F, Lange G-M. The future of the environment. Oxford: Oxford U. Press; 1994.
[51] Røpke I. The dynamics of willingness to consume. Ecological Economics 1999;28(3):399–420.
[52] Schipper L, Grubb M. On the rebound? feedbacks between energy intensities and energy uses in IEA countries. Energy Policy 2000;28(6/7):367–88.
[53] Manne AS, Richels RG. CO_2 emission limits: an economic cost analysis for the USA. Energy Journal 1990;11(2):51–74.
[54] Ophuls W. Ecology and the politics of scarcity: a prologue to a political theory of the steady state. San Francisco: W.H. Freeman & Co; 1977.
[55] Sanne C. Willing consumers – or locked in? policies for a sustainable consumption. Ecological Economics 2002;42:273–87.
[56] Von Weizsäcker E, Lovins AB, Lovins HL. Factor four: doubling wealth – halving resource use. London: Earthscan; 1997.
[57] Owens S, Cowell R. Land and limits: interpreting sustainability in the planning process. London: Routledge; 2002.