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Jevons' paradox

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Abstract

In *The Coal Question* William Stanley Jevons [Jevons, W.S., 1865/1965. The Coal Question: an Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-mines. 3rd edition 1905, Ed. A.W. Flux. Augustus M. Kelley, New York.] maintained that technological efficiency gains—specifically the more "economical" use of coal in engines doing mechanical work—actually increased the overall consumption of coal, iron, and other resources, rather than "saving" them, as many claimed. Twentieth-century economic growth theory also sees technological change as the main cause of increased production and consumption. In contrast, some ecologically-oriented economists and practically all governments, green political parties and NGOs believe that efficiency gains lower consumption and negative environmental impact. Others doubt this 'efficiency strategy' towards sustainability, holding that efficiency gains 'rebound' or even 'backfire' in pursuing this goal, causing higher production and consumption. Because many environmental problems demand rapid and clear policy recommendations, this issue deserves high priority in ecological economics. If Jevons is right, efficiency policies are counter-productive, and business-as-usual efficiency gains must be compensated for with physical caps like quotas or rationing.

Keywords: Technological efficiency; Rebound; Impact; Consumption; Growth; Jevons

1. Introduction

The paper briefly presents today's 'rebound' debate and refers to the relevant literature (Section 2). It then goes into Jevons' (1865) theoretical arguments (Section 3), his analogy with the employment effects of increased labor efficiency (Section 4), and his empirical arguments (Section 5). Open questions in today's debate are how to reconcile the environmental efficiency strategy with growth theory, whether empirical or theoretical work is more urgent, how to integrate consumer behavior into a formal rebound theory, and why the matter is 'paradoxical' (Section 6). The conclusion (Section 7) is that since greater efficiency, ceteris paribus and given latent demand, must raise, not lower, environmental impact, efficiency policies are wrong.

Throughout 'efficiency' denotes the ratio of physical inputs to physical outputs—rather than to

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'services', 'units of consumption', 'economic activity', or monetary gross product.[1] Furthermore, it means technological changes rather than institutional or organizational ones which lower other kinds of input like time and human effort per unit of output.[2] 'Consumption' means the *using up* rather than the 'use' of resources (Boulding, 1949; Princen, 1999, p. 355) and covers pollution as well as resource destruction.[3] A further assumption is that consumption is proportional to environmental impact as understood in the $I=PAT$ equation (impact a function of population, affluence, and technology). No mention is made of the capital and junking costs of efficiency improvements themselves, and the problem of comparing outputs over time (paper letters to e-mail, or horse to plane) is ignored.

2. The current rebound debate

Although previous writers like Hotelling (1931, p. 64) and Domar (1962, p. 605) noted that efficiency, sales, and resource use rise hand in hand, the present debate was re-opened by Brookes (1979) and Khazzoom (1980) and continued by Lovins (1988), Saunders (1992, 2000), Schipper and Meyers (1992), Howarth (1997), Wirl (1997), Schipper and Grubb (2000), Brookes (2000), and Binswanger (2001). Regarding household appliances and explicitly assuming positive price elasticity of demand,[4] Khazzoom's insight was that "…changes in appliance efficiency have a price content…. [W]ith increased productivity comes a decline in the effective price of commodities, and that in the face of lower effective prices, demand does not remain stagnant…but tends to increase" (Khazzoom, 1980, pp. 22, 23). For example, a more fuel-efficient car enables one to drive more.[5] This universally acknowledged phenomenon is called 'rebound' (or feedback, take-back, snap back, or re-spending). A distinction is made between the somewhat measurable 'direct', 'micro', or 'own' rebound effect for goods and services produced more efficiently and the elusive 'indirect', 'secondary', 'economy-wide' or 'equilibrium' rebound effects concerning all other goods and services, present and future, using the same inputs.

To define it one needs the notion of *engineering savings*. This is the difference between two ratios, the first stating energy/material input per unit of product or service *before*, the second *after*, a technologically achieved lowering of input per unit output. Multiplying pre-change demand times this percentage difference yields a physical quantity: when car kilometers and tons of steel can be had for 20% less energy input than before, then 0.20 times the amount previously consumed yields the real amount of energy that *could* be saved. Such gains immediately lower consumption of inputs of material and energy for these outputs; but by both doing more and becoming cheaper, demand for them in turn increases, and output or consumption rise again. If this demand rise is large enough more people consume more; no 'savings' really occur, and we have a paradox. The environmental efficiency strategy—lowering the 'T' factor in the $I=PAT$ equation in hopes of thereby lowering 'I'—must come to terms with this paradox, first identified as such by Jevons.

Rebound analysis thus shows that holding demand constant is gratuitous. The 'savings' is theoretical only, because lower costs heighten demand. 'Rebound' is nevertheless defined as the ratio between the engineering savings in percent and new and old quantities of units consumed, corrected for the efficiency change. If the ratio of post-change demand

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[1] I believe embodied energy, recycling, and product durability are subsumable under either technological or 'consumer' efficiency, and that both the sufficiency strategy of doing without some affluence and the 'decoupling' of services from input are logically separate issues.

[2] For example, economies of scale, trade, education, legal security, property rights, low transaction costs, Taylorite factory-floor measures, management hierarchies, etc. One writer indeed defines rebound as "…the overall effects of technical, organisational, and social progress which increase the efficiency of the economy and give room for more consumption" (Sanne, 2000, p. 494; also Moezzi, 2000).

[3] The debatable suggestion here is sink problems are reducible to source problems: Bad water, air, soil, food, and space would be simply good water, air, soil, food, and space used up. Even greenhouse gases would use up the 'good' of a life-supporting climate. Pollution, degradation, assimilation, degeneration, and 'waste' could be parsimoniously defined in terms of consumption.

[4] In the debate, price elasticity of supply is universally ignored (Schipper and Grubb, 2000, p. 369).

[5] One concise version is that after efficiency gains "…the amount of product or service usually does not stay the same. Because the equipment becomes more energy efficient, the cost per unit of product or service…falls which, in turn, increases the demand for the product or service" (Binswanger, 2001, p. 120; also Howarth, 1997, p. 2).

times the post-change input–output ratio to pre-change demand times the pre-change input–output ratio is greater than 1, one speaks of ‘backfire’ or ‘boomerang’ (Khazzoom, 1980, p. 23; Wirl, 1997, pp. 28–29; Saunders, 2000, pp. 439–40). In judging rebound’s size some bank on empirical study while others focus on theory.[6] Both sides abandon pure empiricism, however, by claiming that after a rise in efficiency absolute consumption is higher than, or lower than, *it would have been otherwise*, i.e. without the efficiency change (Khazzoom, 1980, pp. 22, 31; Brookes, 2000, p. 356; Howarth, 1997, p. 3; Schipper and Grubb, 2000, p. 370; Moezzi, 2000, pp. 525–26[7]).

3. Jevons’ theoretical view

The first chapter of Jevons’ much-cited book (1865, to which all page citations hereafter refer) bears the title “The Opinions of Previous Writers.” Taking this to heart, what exactly did Jevons say? His 460-page argument is unequivocally for backfire. His concern not only for England’s material and intellectual prosperity, but also for posterity, prompts his question of the coal supply’s duration. Since coal is progress, and it will eventually run out, his answer is pessimistically bittersweet (pp. 11–13, 136, 156, 200–201, 274, 460). His theoretical argument that coal-efficiency heightens coal consumption relies on the concepts of *profitability* (Chs. VII, VI, IX), *new inventions and uses* (Chs. VI, VII), and *consumer behavior* (Introduction, Chs. IX, X). He also briefly offers the analogy that labor efficiency causes higher levels of employment (p. 140). His detailed but necessarily indecisive empirical argument correlates efficiency increases and consumption increases (pp. 145–154, 386–391, Chs. XI and XII).

3.1. Almighty coal

His Frontispiece is from Adam Smith: “The progressive state is in reality the cheerful and the hearty state to all the different orders of society; the stationary is dull; the declining melancholy.” He embraced the progressive state for its civilization, amelioration of society, international power, and material wealth (pp. 33, 232, 454–460; Ch. VI) and knew it depended on coal (pp. 1–3, 9, 37, 274–76). Without coal fuel “we are thrown back into the laborious poverty of early times;” to not use the fuel “lavishly and boldly” means “safe smallness, . . .dullness and degeneration,” a stationary period “devoid of intellectual nobility” (pp. 2, 459, 456–457). The Lord Chancellor ought to sit no longer on a bag of wool, but rather a bag of coal (p. 126). Thus it was with “anxiety” that geologists, coal miners, statesmen, and economists were asking the “solemn question” as to the “duration” of coal supplies (pp. 3–6, 412, 454, Ch. XII). Today we ask the oil and pollution questions out of the same anxiety. On the way to his answer Jevons presaged today’s themes of limits to growth (pp. 196–200, 419, 427, 454–55), duty to posterity (pp. 4, 373, 455), renewable and non-renewable resources (p. 201), liv-

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[6] Empirically measured rebounds range from less than 1% to several hundred percent, but never zero or less than zero (Khazzoom, 1989, p. 158; Greene, 1992, pp. 136–137; Wirl, 1997, p. 46; Greene et al., 1999, p. 27; Greening et al., 2000, p. 392; Berkout et al., 2000, p. 431). Some call them insignificant (Lovins, 1988; Schipper and Grubb, 2000; Howarth, 1997; Greening et al., 2000), others significant (Khazzoom, 1987, 1989; Brookes, 1979, 1990, 2000; Greenhalgh, 1990; Greene, 1992; Saunders, 1992, 2000; Sanne, 2000, 2002). Others ignore rebound while asserting or implying that efficiency is environmentally advisable (Stern et al., 1985; Schmidheiny, 1992, pp. 35–36, 40–41; Goodland, 1992, p. 10; Mikesell, 1992, p. 87; Holdren, 1992, p. 42; von Weizsäcker et al., 1997; Vincent and Panayotou, 1997).

[7] Schipper and Grubb’s formal presentation: ‘We define “energy savings” as the product of a future activity level and the difference between the energy intensity at that time compared to the present level. If E is the energy use for a particular activity, then: $E = A \times I$, (1) where A is the level of activity and I the corresponding intensity. After energy saving is implemented, A changes to A' and I to I', and the new energy use is $E' = A' \times I'$. (2) If I' is less than I, energy saved is $A' \times (I - I')$. [$A \times (I - I')$ would be my ‘engineering savings’.] But E' might be larger than E because over the time that I fell to I', A grew by a greater relative amount to A'. Now, the decline in I itself could cause an increase in A' to A'', so that $E'' = I'' \times A''$. We shall look for a rise in A' relative to incomes or output if I falls as a sign of an important feedback effect or structural change “caused” by lower energy intensities or costs’ (p. 369). In this formulation the term ‘energy saved’ *assumes* either that A' is less than A or that if it is greater than A, it is nevertheless not high enough to boost E' above E. Furthermore, if I correctly understand ‘A grew by a greater relative amount’, their own position is that the ‘decline in I itself’ causes A to *fall* ‘by a greater relative amount to’ A''', yielding an E''' smaller than E. They accurately portray the ‘backfire’ position thus: ‘ If saving energy is to lead to greater, not less energy use than otherwise, then either. . . the activities and output for which the savings were made must increase by more than the savings decreased energy use of the overall mix of output must evolve in a two way towards greater, not lower uses than otherwise’(Schipper and Grubb, 2000, p. 383).

ing off capital instead of income (pp. 412, 455), the energy costs of getting energy (pp. 7, 49, 62–63, 72, 77, 196, 198, 200), entropy (p. 412), the sad loss of forests (pp. 37, 183, 249–250, 286, 369–80), and sustainability (p. 454).

Jevons' detailed discussion of British and foreign coal-field geology, mining technology, transportation, and prices leads him to take other researchers to task for overestimating coal's duration—whether 365, 610, 1727, or many thousands of years (Ch. II, pp. 273–75, 280–84[8]). Their "compendious statements" were well-founded except that they overlooked the fact of rising annual demand, or consumption! (p. 19). Two exceptions were John Holland and Edward Hull, Jevons' main source, who nevertheless reassured "…the public at large…that for a long period to come British commerce is not likely to languish, or British household fires to smoulder, for want of that prime necessary of British life—COAL" (Hull, 1905, p. 281; Ch. XXXIII; Hull, 1861, pp. 1–6, 236–37, 241–45; Jevons, pp. 23–31, 195–200, 267–274). Jevons insisted that "…the quantity of coal existing is a less important point in this question than the rate at which our consumption increases, and the natural laws which govern that consumption" (pp. 25, 34–36).

What determines this all-important rate of consumption's increase? Always based on assumptions about coal quality, mine depth, and mining costs (pp. 88–89, 132, 156, 230–32, 274, Ch. IV), three factors were population growth (pp. vi, 9–10, 194–200, 275, 457), newly found or invented applications (pp. 141–142, 152–53, 176, 196, 457–458, Ch. VI), and our wish to consume (p. 25, Ch. IX). But "discovery" was constantly rendering coal "a more and more efficient agent…" (p. 8; also 136, 387–88). The bone of contention was whether this raises, or lowers, total consumption.

3.2. Chapter VII: "*of the economy of fuel*"

"And we ought not at least to delay dispersing a set of plausible fallacies about the economy of fuel…which at present obscure the critical nature of the question, and are eagerly passed about among those who like to believe that we have an indefinite period of prosperity before us" (p. 4). In the dark shadow of future coal shortage many saw the efficient use or "economy" of fuel as a chance to "save" it and postpone the day of reckoning. Thinking of Percy (p. 36), Waterston (p. 22), and Hull (pp. 29–30; Hull, 1861, pp. 238–240) Jevons wrote, "It is very commonly urged, that the failing supply of coal will be met by new modes of using it efficiently and economically. The amount of useful work got out of coal may be made to increase manifold, while the amount of coal consumed is stationary or diminishing. We have thus, it is supposed, the means of completely neutralising the evils of scarce and costly fuel" (p. 137). Countless efficiency strategists today join in with Percy, Waterston, Hull, and Mundella (1878).

After granting the question the status of a "paradox" (also Wirl, 1997, pp. 29, 36, 112; Giampietro and Mayumi, 1998, p. 24), Jevons' dissenting opinion was that "It is the very economy of its use which leads to its extensive consumption" (p. 141). Due to *invention* and *improvement* "…the economy of coal in manufactures" advanced constantly (pp. 8, 152), but "*It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth*….[E]very…improvement of the engine, when effected, does but accelerate anew the consumption of coal" (pp. 140, 152–53). Lowering the input/output ratio causes neither less input for the same output, nor the same input for more output, but more input for more output.[9]

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[8] While even Jevons' projections ran in the order of many centuries, British politics today seems comfortable with the fact that North Sea oil and gas will last another decade or two. On energy alternatives to coal, Jevons, to his posthumous misfortune, acknowledged but underestimated petroleum (pp. 184–185), while Hull bet on electricity (Hull, 1905, pp. 387–393, 434–435).

[9] According to Greenberg, a similar position had been held a generation before Jevons by Richard Jones, namely that 'energy efficiency—whether biological or technological—constituted the true determinant of wealth' (Greenberg, 1990, p. 713). Also presaging some of Jevons' ideas were Lauderdale (1804, pp. 161–165, 184–185); Say (1820, pp. 137, 143, 151) and John Rae (1834), who influenced Jevons through William Edward Hearn (1864) and who posthumously enjoyed Schumpeter's highest praises (Schumpeter, 1911, pp. 12–13) (pp. 19, 23, 292, 258–59 (rebound); 86–87, 115–117, 261–62, 365 (new uses); 164–65, 263 (profit and new capital); 226–229 metallurgy; 242 (pre-efficiency invention); 245–248 (coal and steam); 245, 258–59, 323 (Jevons' social growth); 259 (baking); 310, 321–22 (institutional efficiency)).

The argument is saturated with examples of invention in the "arts" of mining, metallurgy, and engines over some 300 years, as coal and iron out-competed wood, water, wind, human, and horse power (also Cipolla, 1962, pp. 40–52; Clapp, 1994, pp. 161–71; Sieferle, 2001, pp. 61–67, 103, 115–27). The key case was Savery's steam engine of 1698. Intended to pump water out of (coal) mines, the machine however still "wasted" too much heat; without an intervening piston "it was so uneconomical that, in spite of the cheapness of coals, it could not come into common use" (pp. 114–119).[10] That is, the coal-burning steam engine would have to become *more efficient* before it could consume coal. Once improved, this engine "as it were in an instant, put every coal-field, which was considered lost, within the grasp of its owners. Collieries were opened in every district..." (p. 120). Other materials like iron also saw efficiency gains, as with the "substitution...of [lighter] wrought-iron for cast-iron...[which] effected a general economy and advance in the employment of machine power" (pp. 129–130, 372). But what is this vague "general economy" which causes rebound greater than unity in the consumption of iron as well as coal?

3.3. The paradox solved

"Nor is it difficult to see how this paradox arises" (p. 141).[11] The key to his argument is efficiency's effects on *profitability*, *price*, and *demand*: "Economy multiplies the value and efficiency of our chief material...[and] renders the employment of coal more profitable, and thus the present demand for coal is increased.... [If] the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig iron will fall, but the demand for it increases and eventually the greater number of furnaces will more than make up for the diminished consumption of each" (pp. 156, 8, 141; also Jevons, 1871, pp. 254–57). Any given blast furnace gives way to an improved one, and the number of furnaces and the amount of steel rise absolutely. Jevons thus makes rebound theoretically plausible, but he has not yet proven that the amount of coal consumed must "more than" make up for engineering savings.

The solution for Jevons lies somewhere in this step from efficiency to *profitability*, a term both broadly synonymous with productivity and more narrowly covering producers' margins. He notes that "it is a maxim of trade, that a low rate of profits, with the multiplied business it begets, is more profitable than a small business a high rate of profit" (p. 141). The costs of pig iron and even coal fall, upping sales; otherwise no new capital (no new production capacity) is attracted to these sectors, which, however, it manifestly is. This brief argument stays inconclusive, and he immediately adds that the greater demand stems as well from "new activity in most other branches" (pp. 141–42; see below).

One contemporary rendering of this 'profitability' argument states that "An improvement of energy efficiency of capital implies that [the producer] can (a) shift the production factor mix in the long run, and (b) reduce the unit production costs, creating a margin for price setting.... [A] lower sales price may generate additional demand' (Berkout et al., 2000, p. 426). A fuller version states that "...efficiency gains and current incentives often work directly and indirectly *against* resource conservation. Many factors contribute to this counter-intuitive [paradoxical] result, including the price and income effects of technological savings. Improved energy or material efficiency may enable firms to raise wages, increase dividends or lower prices, which leads to increased net consumption by workers, shareholders or consumers respectively" (Wackernagel and Rees, 1996, pp. 127–28).[12]

3.4. New uses, other consumption

Jevons sensed his argument's incompleteness: Profitability causes new demand that is claimed to

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[10] When even endosomatic energy input (Cipolla, 1962, p. 39) is too inefficient, the possibility is that consumption ceases.

[11] Lucky Jevons. Today it is a "theoretical riddle" (Wirl, 1997, p. 29) commanding with good reason special journal issues (*Energy Policy* 28, vols. 6–7; *Energy and Environment* 11, vol. 5). Rebound is like the "Loch Ness monster" sighted by Schipper and Grubb (2000), or rather not sighted.

[12] Joseph Schumpeter, using Lauderdale's example of the loom, also described how efficiency and/or new combinations are conditions for profitability (Schumpeter, 1911, pp. 42–47, 100, 191–92, 208–15).

"more than make up for" lower input intensity, but "…such is not always the result within a single branch…[and therefore] it must be remembered that the progress of any branch of manufacture excites new activity in most other branches, and leads indirectly, if not directly, to increased inroads upon our seams of coal" (pp. 141–142). Khazzoom similarly first acknowledges that "improved efficiency may…result in some reduction in energy consumption," but adds that "An improvement in the efficiency of one appliance influences not only the demand for own end-use, but also the demand for other end-uses. This follows from the fact that end-uses compete for the same overall budget…" (Khazzoom, 1980, pp. 23, 35). Again, current literature distinguishes between micro and indirect or macro rebounds, the latter being an income effect leaving a "consumer surplus" which we use not only to upgrade quality; "the associated increase in the real income allows [us] to raise all kinds of demands including the demand for the service in question" (Wirl, 1997, pp. 41, 20, 26–27, 31, 197; also Wackernagel and Rees, 1996, pp. 128–29; Schipper and Grubb, 2000, pp. 367, 386; Saunders, 2000, pp. 445–48). It is because inputs are thus freed for new uses that single-sector studies are seriously inconclusive.

"Again, the quantity consumed by each individual is a composite quantity, increased either by multiplying the scale of former applications, or finding wholly new applications;" any given "enterprise" has limits, "*But the new applications of coal are of an unlimited character*' (pp. 196–197). "Old applications of coal have been extended, and yet admit of great extension, while new ones are continually being added" (p. 199). Inventions in iron production, like hot-blast smelting, or in metallurgy, like relatively light-weight wrought iron, yield "cheap iron" (pp. 125, 129–30, 405). This "…materially lowered the cost of iron, and, therefore, has led to its employment for many purposes…previously unknown" (p.154; also 152–56, 245, 368–78). Cheap iron in turn raised the demand for coal (p. 372). He quotes Williams that "Whatever, however, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations" (p. 144). Although some new technologies are "of purely organic origin, …many of the more important substitutions are due to coal…. With fuel and fire, then, almost anything is easy" (pp. 134–136). One opinion in today's debate holds that although backfire can happen in "the iron/coal example of Jevons…[such examples] appear to be rare exceptions" (Schipper and Grubb, 2000, p. 385).

One neo-classical model today holds that technologically "augmented" labor and capital mean "…more consumption per worker" (Saunders, 1992, pp. 136–37; 2000, pp. 440, 445, 448). For instance, one study of the replacement of kerosene with solar power for lighting (an efficiency gain even after deducting embodied energy costs) found that this leads both to lighting for more hours, to using the "saved" kerosene for cooking, and indeed to a "…whole range of behavioral responses of the end-users that follow any technical efficiency improvement all of which may, however, not be traced empirically" (Roy, 2000, p. 433). Jevons' perhaps hyperbolic conclusion is that "modes of economy which, in reducing the cost of a most valuable material, lead to an indefinite demand" (p. 390).

Jevons' detailed history of technology covers metallurgy, pumps, plows, coal-cutters, cotton factories, engines, roads and canals, railroads, bridges, water pipes, photography, ice machines, screw steam-vessels, smelting, refining, and forging (pp. 382–386; also Sieferle, 2001, pp. 115–124). He looks as well at "substitutions" and "interdependence" between types of energy and material (p. 385). From this emerges a question about the definition of efficiency. We substitute "a cheaper for a dearer [in the same process], a new for an old process" (p. 136). The former are straightforward efficiency gains, as when coal is lighter and more heat-efficient than wood, or coke bears more ore weight in the furnace than charcoal. But some new processes and products perhaps do not themselves represent efficiency gains, but rather add new denominators, rather like moving targets for calculations of efficiency ratios. He accordingly first posits something new, and then calls efficiency gains "subsequent steps in…improvement" (p. 119). His example is an invention for "determining the longitude of a ship at sea" (p. 113). It is not an improvement in a preceding instrument, although it does improve the efficiency of *shipping*. Railroads were new and open to subsequent gains, but the denominator of ‘transport’—is old.[13] Tying the ideas of profit and new uses together, Jevons repeats, “But no one must suppose that coal thus saved is spared—it is only saved from one use to be employed in others, and the profits gained soon lead to extended employment in many new forms” (p. 155). If efficiency indirectly enables new things, his thesis gains plausibility.

3.5. The consumer

But *why* are new applications of material resources “*of an unlimited character*” (p. 197)? Why are price elasticities of demand positive, why is demand not saturated? These stupid questions arise because till now, the discussion has concerned production. Jevons has shown only that greater economy *enables* higher consumption; real rising consumption also requires consumers. His short chapter “Of the Natural Law of Social Growth” fills this gap by examining the tendencies of population and consumer desires to increase and includes his opinion that “We are getting to the gist of the subject” (p. 194). He first notes that “coal itself is limited in quantity” (p. 198), that a “vague but inevitable limit. . .will stop our progress” (p. 200), and that “We cannot, indeed, always be doubling the length of our railways, the magnitude of our ships, and bridges, and factories” (p. 196). Whether this last opinion would survive a visit to the USA or western Europe today is debatable, but “our *environment*” or “ the powers and capabilities of. . .inorganic nature” have “elastic” yet “inexorable” limits, subject moreover to diminishing returns (pp. 194–98).

These limits contrast, however, with organic nature, including humans. Invoking Malthus and Spencer, his claim is that population and consumption “*tend* to increase. . .[in] *geometrical ratio*” (p. 193; also 245–247; Malthus, 1798, pp. 20–26, 30, 56, 71). His seminal version of the $I = PAT$ formula is that society’s consumption consists of “the number of people, and the average quantity consumed by each” (p. 196). His argument is that “*If* children do as their fathers did. . .” then “*multiplication*” and average consumption both rise; “If our parents doubled their income, or doubled the use of iron, or doubled the agricultural produce of the country, then so ought we, unless we are changed either in character or circumstances” (pp. 193–94, 232, 275). The “purposes” and “needs” driving invention (p. 113) come from our reservoir of unmet demand whenever costs go down. These are, then, the “natural laws which govern. . .consumption” (p. 25) and a “natural law of growth, or multiplication in social affairs” (p. 275). Not only our numbers, but also our “social advance” tend to grow “ad infinitum” (pp. 194, 195; also Hearn, 1864, pp. 68, 100–102, 123–133, 178–185; Wackernagel and Rees, 1996, p. 127). We choose more output over less input and more free time. With cheap coal and “skill in its employment, . . .[the English] are growing rich and numerous. . .” (pp. 199–200).

Given widespread poverty, population growth, new products, and competitive consumption,[14] sizeable latent demand need not be belabored. As an assumption, though, or factor in a consumption function, it should be made explicit. Brookes, for instance, writes that “. . .it has been claimed since the time of Jevons that. . .for a resource to find itself in a world of more efficient use is for it to enjoy a reduction in its implicit price with the obvious implications for demand” (2000, pp. 356–57). Obvious or not, a *proof* of backfire is impossible without this demand. Both previous consumers and marginal consumers (Wirl, 1997, pp. 19–20, 29–32; Brookes, 2000, pp. 360, 362) must be invoked—or denied, as in one argument against significant rebound that explicitly assumes saturation (Grubb, 1990, pp. 39–43, 187, 242). Were we only seeking to lower the costs in our cost/benefit ratios, efficiency would save resources; when we seek as well to raise benefits, rebound is positive and maybe >1.

3.6. The clincher?

Jevons’ strongest theoretical point arises from his musings over Savery’s failed and Newcomen’s somewhat more efficient but still voracious and noncom-

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[13] Jevons’ full-blown theory of new discoveries has three “conditions of invention”: first a “purpose” or “need”, then a “principle” of knowledge, and thirdly “the material, power, and skill for embodying this principle in a. . .construction.” A steam-engine is such a construction—the thing with a price, input costs, and profitability (pp. 112–19, 148–49; Hearn, 1864, pp. 168, 187).

[14] Thorstein Veblen’s analysis of efficiency, emulation, and status consumption offers a psychological explanation for Jevons’ position (Veblen, 1899, pp. 25, 32,73, 99, 110–11, 156–63, 208, 227, 241, 342; also Alcott, 2004).

petitive engine. Because the water-wheel had “been carried near its mathematical maximum of efficiency,” coal-burners had a hard time (p.177). Brindley’s opinion of the Newcomen engine was that “. . .unless the consumption of coal could be reduced, the extended use of this steam-engine was not practicable, by reason of its dearness, as compared with the power of horses, wind, or air” (p. 143). (Note that replacement of labor by capital, of endosomatic by exosomatic input, also continues at today’s higher technological levels.) With the Savery engine, though, “. . .as he allowed the steam to act straight upon the water, without the intervention of a piston, the loss of heat was tremendous. Practically, the cost of working kept it from coming into use; *it consumed no coal, because its rate of consumption was too high*’ (pp. 143, 118). That is, had efficiency not led to lower and lower “rates of consumption”, we would consume no coal!

Jevons is asking his ‘economy’ adversaries what would have happened to population and consumption had the steam engine not progressed from Newcomen to Watts and further. Is 1865’s level of production then even conceivable (pp. 152–54, 265–79)? The same question today is: If we assume a fuel technology frozen at Watt’s thermal efficiency of about 4%—even imagining any number of institutional and factory-floor efficiency gains—is it plausible that 6 billion people would be living at today’s affluence (Brookes, 2000, p. 359)? Or, remember that supporters and opponents of Jevons both compare a scenario *with* and *without* technological efficiency gains, opponents claiming that absolute consumption is higher in the scenario *without* them. But if in this scenario we assume the *same* increase in population and affluence that has really obtained, then at Watt’s level of material/energy intensity charcoal, coal, oil, and gas would all be long gone. But positing that not only T but also $P \times A$ remain the same begs too many questions. Both sides must explain the real rise in population-times-affluence. For this Jevons can invoke technological efficiency gains; his opponents cannot. Only if today’s $P \times A$ is remotely possible at ‘Watt’ technology is the low rebound position plausible. Jevons insisted that “. . .it cannot be supposed we shall do without coal more than a fraction of what we do with it” (p. 9; Brookes, 2000, p. 359).

A corollary is that if “economy” lowers total consumption, diseconomy or efficiency *losses* should raise it. Take an efficiency *decrease* and compute engineering *losses* by keeping demand constant and multiplying by the higher input–output ratio. Input prices rise, lowering demand again in a sort of reverse rebound. The anti-Jevons position (Schipper and Grubb, 2000) would then say yes, consumption did go down, but less than it would have (“otherwise”) *without* the efficiency decrease. Curiously, though, no one would deny that straightforward price increases lower consumption. Thus, for Waterston et al. to believe that economy “spares” fuel, they must also believe that as inputs become more *costly*, we consume more of them.

4. Analogy: the economy of labor

Jevons’ brief argument from *analogy* concerns time or labor efficiency. “As a rule, new modes of economy will lead to an increase in consumption according to a principle recognised in many parallel instances. The economy of labor effected by the introduction of new machinery throws labourers out of employment for the moment. But such is the increased demand for the cheapened products, that eventually the sphere of employment is greatly widened” (p.140; also Petty, 1675, pp. 249–250; Cipolla, 1962, pp. 65, 105; Khazzoom, 1980, p. 23; Clapp, 1994). Seamstresses for instance have higher wages due to the sewing machine (p. 140). In agriculture of course “Labour saved is rendered superfluous. . .because the area of land is limited and already fully occupied” but other economic sectors then absorb this labor (pp. 243–244). In coal mining or the iron trade, he notes that although “hand labour is still further replaced by mechanical labour” (p. 153), population and employment in towns and around collieries rose greatly (pp. 130–131, 213–218, 277–278).

Khazzoom also offers this analogy, substituting “labor made redundant” for “energy saved” (both temporarily) (Khazzoom, 1987, p. 87; Khazzoom, 1980, p. 23). Greenberg relates the calculations of Owenite John Brooks in 1836 that the mechanical and chemical power of Great Britain and Ireland was doing the work of 600,000,000 people; it in no way follows, though, that even a thousandth of a percent of this number was therefore “out of work” (Greenberg, 1990, p. 711). Her study of early 19th-century attitudes toward "technological unemployment" concludes that ever more productive machines were seen to supplement, rather than supplant, human power (pp. 699–703, 712). In light of the huge population increase over the last two centuries, it seems that neither human beings nor fossil fuels, in spite of huge productivity increases, remained unemployed.[15] Again, regarding time/labor input, the anti-Jevons 'savings' position must claim that *without* labor efficiency gains rises in work and population would have been *even greater*!

One reason that the case of labor efficiency was "recognised" was perhaps Say's well-known proof in his fourth Letter to Malthus (1820). He endorses Malthus' argument that technological improvement lowers cost and that both consumption and employment in the newly more efficient or "quickly producing" industries rise above previous levels, e.g. in textiles and printing (pp. 127–129). He criticizes Sismondi, whose logic failed to appreciate that efficiency raises purchasing power, scathingly predicting that his diagnosis of unemployment would earn him the ridicule of posterity (pp. 138–144). He then adds to Malthus' argument: Even if demand is saturated for the more efficiently produced product, what is today called an income effect "costlessly" augments consumption (pp. 129–130, 135, 151). He quantifies the example of efficient, mechanical flour milling, whereby the laid-off grain-grinders must and will *do something else* (pp. 133–134, 140).

Thus foreshadowing Jevons' argument from new applications, he says that people will make and buy *new products* as efficiency improvement enables "progress" to spread to other industries (pp. 137, 143, 151). Say's observation is that after any sort of efficiency gains, at least the same amount of flour, workers, energy, ability, and tools remain (pp. 137, 140). Paralleling Jevons' 'profitability' argument, he notes that capital gets formed only if greater production ensues—and capital formation is a fact (pp. 146–150; also Schumpeter, 1911, pp. 208–215). By taking the long view (pp. 132–133, 142–144), surpassing single-sector analysis, and taking the marginal consumer seriously, Say demonstrates *growth* effects of the *perfectionnement d'les arts*. He even hints that the matter is paradoxical: the augmentation of "employment and population" is *survenue* (p. 142).

5. Jevons' empirical argument

The duration of coal sources depends for Jevons' not only on how much there is and at what depth, but also on consumer behavior; this derives in turn from our numbers, our wanting to consume at least as our ancestors did, and how economically we used these sources. Tables throughout the book show that "In round numbers, the population has about quadrupled since the beginning of the nineteenth century, but the consumption of coal has increased sixteenfold, and more. *The consumption per head of the population has therefore increased fourfold*' (pp. 196, vi, 457). Covering all sectors of the British economy, his figures show large rises in both pig iron and coal consumption (pp. 246, 262–265, 280). He then establishes a *correlation* between this and rises in efficiencies. In terms of pounds of coal per horse power per hour, he traces the more than tenfold increase in steam engine efficiency from Newcomen and Watt to Woolf and Elder (pp. 145, 261–271; also Greenberg, 1990, pp. 703–705). Or in smelting: The foregoing decrease in coal use per ton of pig iron "*to less than one-third of its former amount, was followed, in Scotland, by a tenfold total consumption*, between 1830 and 1863 in Scotland..." (pp. 154, 387–388). Efficiency and total consumption had risen together, moreover, the latter more than the former. His opponents today reply that this proves nothing: Other factors cause the growth, and but for the greater economy, even more would have been used up.

While efficiency gains were attested by all, Mundella was one who disputed their effects in raising consumption, claiming that although from 1869 to 1876 efficiency and pig iron production both went up, consumption of coal "used in its Manufacture" went down (1878, pp. 90, 112). He identified efficiency gains through better furnace construction, use of waste heat, and in general hotter and better blasts (Bessemer and Siemens), concluding that "There is no evidence showing that the economy of fuel in the making of pig iron, and the consequent reduction in price, has led to the manufacture of more iron, by which more coal would have been consumed, as Mr.

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[15] Another analogy is with agricultural input and output per square meter: Do efficiency gains mean we take land out of cultivation?

Jevons [in his "remarkably able work"] argues" (pp. 112, 89). In his reply to Mr. Mundella's "fairest" treatment of the subject, Jevons stuck to his guns. But the only numbers he crunched concerned whether coal consumption rises 2.5% or 4% every year, reiterating his point that at neither rate could the increase go on forever (Mundella, pp. 118–119).

Mundella's argument raises three questions still haunting the debate. 1) The time period considered: While his text looks at 1869–1876 only, and its 5% fall in coal consumption "in the manufacture of pig iron" (p. 90), his supporting Table F covers 1840–1876, showing a fourfold hike (p. 112); he believed that the trend had recently reversed. 2) He was only looking at coal's consumption "in [pig iron] Manufacture"! Actually, the Table's caption records "Coal used in its Manufacture" whereas the Table itself leaves out the word "its" (p. 112). His Tables B, C, and D showed, in fact, large overall use increases from 1660 to 1876 (pp. 109–111). But whatever the numbers, his single-sector study is ignoring new uses and thus today's income, substitution, or general equilibrium effects. 3) He restricts himself to Britain (while Jevons at least devotes Chs. XIII–XVI to the international scene).[16]

Since correlation does not prove causality, both sides need theory. Note that Mundella does concede the link between "economy" and "the consequent reduction in price," but not the rebound step to raised demand (p. 112). Jevons' reply to Mundella also re-emphasized Cairne's thesis "that the cost of production was not the cause, but the effect of the efficiency of production" (1878, p. 118). In sum, Jevons establishes growth of population, agricultural and manufactured goods, and coal consumption alongside higher "economy" or productivity. Today as well nobody doubts such worldwide increases over, say, 250 years. One treatment for instance both attests to these statistics and warns of the complexity of the concept of "global energy intensity" (Smil, 2003, pp. 6–7, 49, 65–81). But to establish the causal arrow, I think Jevons is asking in his chapter on "social growth" why we seek efficiency in the first place. Surely to consume more easily and cheaply, but also to consume more.

6. Discussion

Jevons' view is compatible with later production functions and theories of economic growth[17] that attribute much to technological change as opposed to mere changes in labor productivity or population size (itself in need of explanation). One version sees "two obvious candidates" to explain growth, namely "technological progress and increasing returns to scale…. I reckon that technological progress must be the more important of the two in real economies…. The natural rate of growth [in the model] is now the sum of the rate of population increase and the rate of technological progress" (Solow, 1970, pp. 33–35, 38; also Schumpeter (1911); Schurr (1982, 1985). One list of terms for this strong factor ranges from "output per unit of input" through "efficiency index", and "total factor productivity" to "measure of our ignorance" and "the Residual" (Domar, 1961, p. 709). Anticipating the rebound concept, the same author states that a "rapid growth of [Kendrick's technological progress] Index in any industry reduces the prices of its output, and thus stimulates sales" (Domar, 1962, p. 605). Notwithstanding the difficulty of deriving an absolute quantity (consumption) from a ratio (efficiency), the theoretical question is whether the view that rebound is lower than 1 is also compatible with this consensus.

Recall that today's debate compares paths of total consumption with, and without, technological efficiency change—far more explicitly than in Jevons' treatment (Saunders, 1992, p. 135; Schipper and Grubb, 2000, p. 370). In the anti-Jevons position, both paths posit growth, even the one with frozen technology. But what, then, is to cause this posited growth (Brookes, 2000, p. 359)? Population? Institutional efficiency gains of all sorts? Schipper et al. (1996) indeed name exactly these three effects—population,

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[16] My father's belief that 'figures can't lie, but liars sure can figure,' is assumed to apply to neither side. Domar (1962, p. 602) wrote, "Like politics, empirical work is the art of the possible".

[17] More accurately: explanations of the exact size or scale of the economy, whether growing or shrinking.

structure, and intensity—conceding that although the intensity effect lowers the costs of "energy services", growth is mainly due to "structural" effects (1996, pp. 192, 174). Another analysis (of US data from 1929 to 1970) concludes with the calculation that the "Khazzoom–Brookes hypothesis…must assert that improvements in energy efficiency were responsible for a full 29% of the increase" in GNP during a particular span of 41 years, but that "Claims of this sort, however, seem palpably implausible" (Howarth, 1997, pp. 2–4). But the author offers us neither a criterion of 'plausibility' nor a clear identification of the factors that do account for GNP growth. Note that whatever they are, these factors must be extremely strong: they must not only do without technical progress, but must also *compensate for* it. Thus, while growth proponents and neutral analysts universally know that both technological and institutional efficiency must figure in the recipe,[18] some who do not welcome the environmental impact of growth claim that efficiency will, ceteris paribus, reduce the size of the material economy.

Regarding empiricism, Jevons early on tells us that he "must also draw attention to principles governing this subject, which have rather the certainty of natural laws than the fickleness of statistical numbers" (pp. 6, 198–99). Of course the book then delivers pages of fickle numbers, but they do not suffer any worse from methodological problems than today's: 1) limitation to certain time periods; 2) limitation to certain sectors; and 3) limitation to certain countries or groups of (usually OECD) countries. Following Jevons quite strictly, most researchers lament these acknowledged inadequacies while continuing to conduct micro studies (Grubb, 1990, pp. 195, 235; Howarth, 1997, p. 4; Greene et al., 1999, p. 28; Brookes, 2000, pp. 358, 365; Greening et al., 2000, p. 392; Binswanger, 2001, p. 124). Short of studies of two non-trading economies alike in every respect except technological change, the debate still seems heavily dependent on theory.

Another open question concerns how, exactly, to integrate into a formal theory the consumer's high price elasticities of demand—be these "natural" or somehow more contingent. Marginal consumers must at any rate be added. And finally, what is so paradoxical about this matter? Perhaps that if an efficiency gain causes a drop in the price of an input of 10%, and this input makes up 10% of product cost, then costs are down a mere 1%. Many (single-sector) studies indeed compute rebounds of 15% to 50%. Or perhaps that individually, if I replace my open fireplace with a ceramic stove, I simply cut less firewood back of my house, 'saving' time and wood. The macro result remains thus 'counter-intuitive'.

7. Conclusions

Jevons writes with the same uneasiness we feel today about overburdening the planet and exhausting its resources. Is greater material or energy efficiency a remedy, as many optimists and some environmentalists believe? "This is a question of that almost religious importance which needs the separate study and determination of every intelligent person" (p. 14). He reluctantly answered with 'No.' Today ecological economics must give advice on this surely not unanswerable question—the more so if Impact is growing rapidly—but a firm consensus is lacking. Certainly, theoretical work must see whether the environmental 'efficiency strategy' is reconcilable with standard growth theory. One certain conclusion, though, is that if Jevons is right, then efficiency policies are simply counter-productive. Even taxes on fuel or CO_2 will be compensated by efficiency increases, and moreover they face the problem that tax revenue also gets spent on material and energy (Wackernagel and Rees, 1996, p. 20).

By enabling population and affluence to rise, both business-as-usual and policy-induced efficiency gains are partial causes of environmental stress. Indeed, efficiency, sufficiency, and population strategies all face the problem that the $I = PAT$ equation is transitive: all right-side factors influence each other, leaving impact the same or higher. This enhances the attractiveness of directly lowering impact through rationing and quotas, whether of resources or emissions (as in the 'Kyoto' agreement) (Daly, 1973, pp. 337ff., 1996, p. 15; Wackernagel and Rees, 1996, p. 129; Brookes, 2000, pp. 363–64; Rudin, 2000). Politically unfashionable though they may be—Jevons himself denied

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[18] For instance, the mainstream in Switzerland today does not doubt that the country's bilateral agreements with the EU will put it back on the path of 2% annual growth.

that "the consumption of coal can be kept down in our free system of industry. . ." (p. 136)—ecological economics should once again take resource rationing seriously.

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