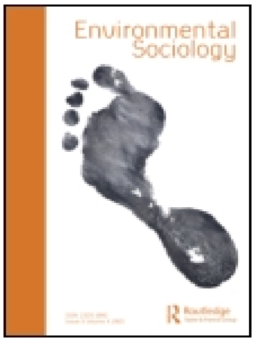

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Understanding the Jevons paradox

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There is considerable debate about the connections between efficiency and levels of resource consumption, particularly about the Jevons paradox and the rebound effect. To help clarify a variety of misunderstandings, we distinguish between the empirical claim that efficiency is often associated with rising resource consumption and the causal claim that efficiency leads to greater resource use. We show that at a variety of levels, a positive correlation between efficiency and resource consumption is common, suggesting that there is something to be explained. We then present various reasons that may explain these associations, some of which do not suggest a direct causal link between efficiency and consumption, but rather a connection through other mediating factors, and some of which do suggest a causal connection. We note that political economic theories propose that the effect of efficiency on consumption levels is not necessarily immediate and direct, but rather due to how it affects developmental pathways. We present an empirical analysis, using panel data on nations, which shows that more efficient nations tend to have higher rates of growth in electricity and overall energy consumption and carbon dioxide emissions, consistent with what political economic theories suggest.

Keywords: Jevons paradox; rebound effect; efficiency

Introduction

There is an ongoing assessment in environmental sociology and other environmental fields of how improvements in the efficiency with which natural resources are used affect the overall levels of resource consumption. There are theories that suggest improvements in efficiency, driven by advances in technology and organizational restructuring, have the potential to dematerialize production and provide for an ever-expanding economy with lower energy use and declining carbon dioxide emissions (Hawken, Lovins, and Hunter Lovins 1999; Andersen 2002; Fisher and Freudenburg 2001). While on the surface it seems obvious that improvements in efficiency must help curb resource use, since by definition improved efficiency reduces the amount of resources used per unit of production or consumption, there is a considerable amount of evidence that rising efficiency is often correlated with rising resource use at various scales and in various contexts through its connection to growth of production and consumption.

Debates centred on the rebound effect and the Jevons paradox (Alcott 2005; Gillingham et al. 2013; Polimeni et al. 2008) have often focused on whether the nature of the relationship between efficiency and resource use is one where efficiency *causes* total resource consumption to rise. However, owing to the multiple instances in which improvements in efficiency are associated with more resource use and the many explanations given for these phenomena, there is considerable confusion in these debates about what is meant by the Jevons paradox and the rebound effect. There are a number of insightful reviews and assessments of the Jevons paradox and the rebound effect (e.g., Gillingham, Rapson, and Wagner 2015; Greening, Greene, and Difiglio 2000; Polimeni et al. 2008; Sorrell 2007, 2009), but they have typically not been connected with debates in environmental sociology. Our aim here is to clear up some of the confusions that exist about efficiency by presenting various meanings and implications of the Jevons paradox and the rebound effect, and to present a new analysis to assess one aspect of how efficiency may affect resource use. We connect this assessment and analysis with debates in environmental sociology that either explicitly or implicitly deal with the nature of efficiency. First, we present a brief discussion of how theories in environmental sociology assess the implications of efficiency improvements for resource conservation. Second, we present a brief overview of the Jevons paradox and the rebound effect, explaining the subtle differences in interpretations of these terms. In particular, we focus on distinguishing claims about association versus those about a causal connection between efficiency and resource use. Third, we present some examples from the scholarly literature and empirical evidence to establish that there is commonly a positive association between efficiency and resource use, which calls out for an explanation. Finally, we present an original analysis that addresses one way that efficiency may lead to rising resource consumption.

Efficiency in environmental sociology

In environmental sociology, discussions about efficiency often revolve around assessments of the extent to which modernization, science, and technological developments

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can help societies overcome environmental problems. Early work in the sub-discipline, from both human ecological (Catton 1980) and political economic (Schnaiberg 1980) theoretical perspectives, criticized the widespread expectation that modern societies would be able to overcome the challenges of resource shortages, pollution, and ecosystem deterioration via scientifically driven technological advances. As we explain in more detail in subsequent sections, the political economic theorists in particular identified technological development as a central part of the forces driving economic growth and attendant environmental degradation (Schnaiberg 1980). From this perspective, the efficiency of production was a means to expand the scale of production and profits, so technologically driven efficiency improvements would not typically translate into ecological reform without radical social change.

Ecological modernization theory in many respects provides a counter-point to political economic and human ecological theory. Ecological modernization theory is grounded in the premise that processes of modernization, rather than being inevitably the cause of environmental problems, can lead to environmental sustainability without radical social change. One of ecological modernization theory's leading proponents, Arthur Mol, emphasizes the contrast between ecological modernization and other prominent theories in environmental sociology, noting the former 'identifies modern science and technology as central intuitions for ecological reform (and not in the first place as the culprits of ecological and social disruption' (1996, 313). The supposed potential for technological innovation to solve environmental problems has been identified by several scholars as the 'linchpin' of ecological modernization (Fisher and Freudenburg 2001, 702; Milanez and Bührs 2007, 572). Cohen notes that transitioning to 'the use of cleaner, more efficient, and less resource intensive technologies' is a 'key element' of ecological modernization's expectations about environmental reform (1997, 109). Andersen makes explicit the view that efficiency, measured as pollution or resource consumption per unit of production, is a central concern of this perspective, stating that 'changes in CO_2 emissions relative to GDP [are] a rough indicator for the degree of ecological modernization that has taken place' (2002, 1404). Reflecting this technological Prometheanism, Mol and Spaargaren declare the 'irrelevance of "more" or "less"' with regard to the scale of production or consumption, since they see technology allowing society to overcome natural limits (2004, 261).

Assumptions about the efficacy of technological advances and efficiency in bringing about environmental improvements are widespread in environmental sociology, even beyond supporters of ecological modernization theory. For example, Roberts, Grimes, and Manale argue that to avoid continued global warming 'it will be necessary to improve the quality and energetic efficiency of the infrastructure of production, distribution, and consumption' in nations around the world (2003, 304; see also; Roberts and Grimes 1997). Although this optimism about efficiency and technology to solve environmental problems has been criticized (e.g., Bunker 1996; Clark and Foster 2001; York 2006, 2010), no consensus has been reached among environmental sociologists about how to understand the role of efficiency in environmental degradation or reform.

The rebound effect and the Jevons paradox

One and a half centuries ago, William Stanley Jevons (1865) observed that a counter-intuitive association characterized the history of the industrial era where coal consumption increased as coal-fuelled steam engines became more efficient. In fact, the positive association between efficiency and resource use, which has come to be known as the Jevons paradox, has been observed with various resources and technologies at multiple scales and in many contexts (Alcott 2005; Clark and Foster 2001; Polimeni et al. 2008; Sorrell 2007, 2009; York 2006). The frequency of the paradoxical association and the explanations for it are highly contested, as are the implications of the phenomenon for approaches to addressing environmental and resource problems.

The Jevons paradox can be seen as a subset of phenomena captured under assessments of the 'rebound effect,' which has garnered attention in economics (Greening, Greene, and Difiglio 2000). The rebound effect refers to any circumstance where efficiency improves by X%, but resource consumption declines by something less than X% or increases. So, for example, if the fuel efficiency of a car improved 10% and, in practice, fuel use by that car declined by only 8% (perhaps due to more driving in the face of slightly lower cost per distance travelled), there is a rebound effect, where some of the anticipated reduction in fuel use did not occur (i.e., a lost benefit of 2%). This is often expressed mathematically as the ratio of the 'lost benefit' to the expected benefit. So, in this example, there is a 20% [(10–8)/10 = .20, or 20%] rebound. The Jevons paradox occurs when the rebound effect exceeds 100%, meaning that there was an actual increase in resource consumption, not just the loss of some of the potential benefit. For example, if the 10% improvement in fuel economy corresponded with a 2% *increase* (i.e., a − 2% decrease) in fuel use, the lost benefit is 12%, so the rebound is 120% [(10–(−2))/10 = 12/10 = 1.20, or 120%].

The terms the 'Jevons *paradox*' and the 'rebound *effect*' can lead to misunderstandings about what is implied by invoking either term to describe a situation. For the sake of clarity, we think it is important to recognize that *paradox* refers to a counter-intuitive outcome or an *apparent* contradiction, not a logically unresolvable contradiction. It does not imply that the outcome is unexplainable. In fact, identifying a paradox is a call to find an explanation, which is why noting instances of the Jevons paradox is valuable for furthering our understanding of economic and political processes. One important point here is that the word paradox does not suggest what the explanation is for the association between efficiency and resource consumption – e.g., observing an instance where resource use grows as efficiency improves (the Jevons paradox) is not the same as asserting that improvements in efficiency are the *cause* of growth in resource consumption. There may be multiple reasons for the correlation between efficiency and resource consumption in any particular context.

Unlike the term *paradox*, the term *effect* in 'rebound effect' does imply that efficiency has a causal influence on resource use beyond the obvious immediate resource savings of the efficiency itself. Across the wide literature on the rebound effect and the Jevons paradox, which is too extensive for us to review here, there is inconsistency in how these terms are used. It is unclear in many discussions whether characterizing a situation as an example of the Jevons paradox is meant to indicate that efficiency is what caused resource use to rise. Likewise, in the case of noting a rebound of less than 100%, it is often unclear whether efficiency itself stimulated increasing consumption, which took back part of the potential resource conservation gains.

To help overcome this lack of clarity, we propose using the term *association* for the empirical identification of a situation where efficiency is either positively correlated with resource consumption or resource consumption does not decline as much as efficiency improves. The term *effect* should be saved for an assertion that efficiency is the *cause* of changes in resource use, while recognizing that there may actually be multiple pathways by which efficiency influences resource use, so perhaps it is better to speak in terms of effect*s*. So, broadly, we can speak of the 'rebound association', of which the 'Jevons association' is a subset where the rebound in greater than 100%. When there is an assertion, based on theory and/or empirical analysis, that there is a causal connection between efficiency and additional consumption, we may then speak of effects. So as not to create too many terms, we will use the traditional term 'rebound effect' to refer to assertions that efficiency causes rising resource consumption, and this effect may or may not be sufficiently large to lead to a Jevons association (as opposed to a rebound association where the rebound may be less than 100%). The term 'Jevons paradox' can be used in place of the 'Jevons association,' or more broadly to capture both the association and the causal assertion that efficiency spurs production and consumption. It is important to note, as we will explain later in this paper, Jevons (1865) did argue that efficiency was the cause of rising coal use, so in addition to observing the association, he also identified a causal process, which appropriately can be called the Jevons effect.

We emphasize that it is very likely that not one but rather many processes account for observed instances of rebound (including Jevons) associations. Furthermore, these processes likely vary across time, place, scale, and particular resource or technology. It is probable there are in fact many potential cause–effect relationships that take part in explaining any one instance of rebound association. Here, focusing on the most troublesome end of the rebound spectrum, we will outline the possible explanations for an observed Jevons association, where high efficiency is associated with high levels of resource consumption.

First, the association may be incidental (e.g., chance co-trending), where factors unrelated to efficiency gains led to the high levels of resource consumption. In this type of a situation, efficiency itself could be suppressing resource consumption, but it is simply insufficient to overcome other forces that are affecting resource consumption. If this is the case, then efficiency is still worth pursuing since it does help reduce resource consumption independent of other factors.

Second, as suggested in the literature on the Jevons paradox and the rebound effect, through a variety of mechanisms, potentially both direct and indirect, efficiency spurs production and consumption, and does so enough to overwhelm the direct gains from efficiency itself (i.e., a rebound effect greater than 100%, as in the Jevons association). Direct effects include the reduction in price per unit of production or consumption that comes with efficiency, which stimulates more production or consumption (Greening, Greene, and Difiglio 2000; Gillingham et al. 2013). Indirect effects may stem from how the money saved, either by producers or by consumers, from improvements in efficiency is spent, where the goods and services purchased with the savings necessitate resource consumption (Greening, Greene, and Difiglio 2000; Gillingham et al. 2013; Sorrell 2009). There may also be more radical indirect effects, where efficiency leads to a structural transformation of production/consumption processes, setting a pathway to future reliance on high levels of resource consumption (Greening, Greene, and Difiglio 2000; Zehner 2012). We address the latter issue in more detail below. If it is the case that efficiency through any or all of these routes spurs growth in resource consumption in excess of the immediate saving from the efficiency itself, then efficiency is contributing to resource problems and runs counter to the goal of resource conservation.

Third, efficiency and the scale of production and consumption may be driven by the same process, so although logically independent from one another, they are connected through structural factors and, therefore, may change over time for similar reasons. For example, as political economists like Schnaiberg (1980), O'Connor (1988), Bunker (1996), and (Foster 2000; Clark and Foster 2001) suggest, in capitalist societies, corporations have the aim of maximizing profits, which can be achieved in two primary ways. First, it can be achieved via reduction of the costs of production, of which improving efficiency of resource use – i.e., using fewer resources to produce the same amount of goods and services – is an example. Second, profits may be increased by producing and selling more goods and services. Economic actors in capitalist societies will typically seek to maximize profits by pursuing both of these methods, so that efficiency and resource use will grow together and reinforce one another, since the rise in profits they generate can be reinvested in further expanding production and consumption and improving efficiency. Of course, the decisions to improve efficiency and to expand production are separate decisions, even if they may have the same motive (profits), so there is no necessary reason they must always go together. Therefore, improving efficiency alone could help in conservation if it is not coupled with processes that lead to the expansion of production.

It is also important to recognize that there are paradoxical phenomena beyond resource use that may be connected to some extent with the processes that lead to the Jevons association. For example, Schor (1993) has shown that in the United States over the past several decades, despite dramatic gains in worker productivity, where one worker can produce per hour several times more than her/his predecessors could years before, Americans have not seen an appreciable decline in the hours they work per week, and in fact have experienced a decline in leisure time. This is very much like the Jevons association, since worker productivity is a measure of labour efficiency, and it seems intuitive that if workers are becoming more efficient they should need to work less, when in fact often the opposite is the case. This is likely connected to some of the processes we touched on above and will discuss more further where capitalist elites use gains in efficiency – of both resource use and labour productivity – to expand production and increase profits, rather than to conserve resources and provide leisure time to workers.

We suggest that none of the three types of processes we identify above is the single, universal explanation of instances of the Jevons association, but rather that all of these phenomena may occur in different circumstances, which points to the need for researchers to attempt to identify the causal processes that lead to a particular instance of an observed Jevons association. In the next section we show that the Jevons association is quite common in many types of circumstances, which points to the importance of seeking explanations for it.

The Jevons association is common

The Jevons association is empirically common at various scales. At the national level, the positive association between the energy efficiency of the economy and energy consumption can be established in both cross-national terms and as a pattern over time in many individual nations. Taking China as an example, since it is one of the most important nations in the world when considering energy use due to its large population and rapidly growing economy, Figure 1 shows the trend in energy efficiency (GDP/energy use) and energy use per capita from 1971 to 2011. It is clear in the figure that, rather than moving in opposite directions, energy efficiency steadily improves over time, where the amount of energy used per dollar of GDP declines by nearly a factor of 5 (i.e., efficiency improves five-fold) between 1971 and 2011, while energy use per capita steadily marches upward, growing by more than four-fold (and total energy use grew by a factor of 7 over this period). In fact, the correlation over this time period in China between energy efficiency and both energy use per capita and total energy use, whether the variables are either in original units or in logarithmic form, is very high, being .89 or more (see Table 1). While not all nations show such a strong pattern, it is fairly common for many nations and for various types of resource use (York 2010; York et al. 2011; York, Rosa, and Dietz 2009), and the global economy as a whole for a long

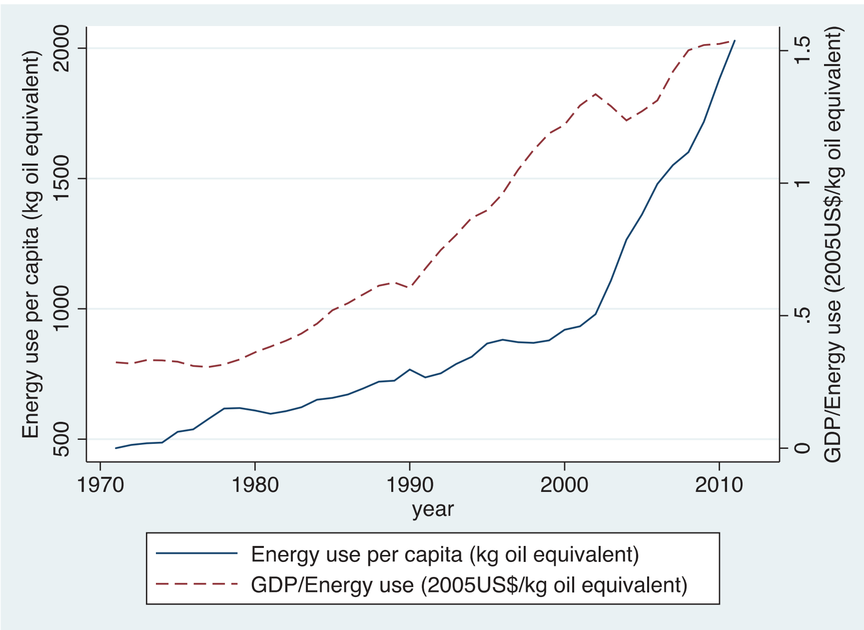

Figure 1. China's energy use per capita and energy efficiency of the economy (GDP/Energy use), 1971–2011.

Table 1. Correlations of energy use per capita and total with energy efficiency (GDP/energy use) for time-series in China (1971–2011) and across nations (2010).

	Unlogged variables	Logged variables
	Pearson's r	Pearson's r
China, 1971–2011 (N = 41)		
Energy use p.c. and GDP/ energy use	.892***	.910***
Energy use total and GDP/ energy use	.915***	.945***
Cross-national (N = 131)		
Energy use p.c. and GDP/ energy use	.158†	.360***
Energy use total and GDP/ energy use	.007	.071

Note: *** $p < .001$ (two-tailed tests) † $p < .05$ (one-tailed test).

time has had a tendency to become more efficient while using ever more resources (Bunker 1996).

There is also a clear Jevons association when looking at cross-national data. For example, for 2010, there is a significant positive association, although not nearly as strong as the one for time series in China, between energy efficiency and energy use per capita (in both original units and logarithmic form), showing that the most efficient nations tend to have the highest levels of energy use (see Table 1). The cross-sectional association between energy efficiency and total energy use is also positive, but only weakly so and not significantly. This is similar to (but not as strong as) the cross-national association between the ecological footprint efficiency and the ecological footprints of nations identified by York, Rosa, and Dietz (2004).

The Jevons association is especially common at the national level in part because of structural changes that occur in economies as they develop. Efficiency in the macroeconomic sense (e.g., GDP/energy use) often improves as nations develop not singularly because of changes in the efficiencies of the technologies they use, but because of changes in the structure of the economy, where it is common to get a larger share of GDP from less energy-intensive sectors (e.g., service instead of manufacturing) as nations become affluent. It is well established that economic growth is a key driving force of energy consumption and pollution emissions, although this effect diminishes to some degree at high levels of affluence (Jorgenson and Clark 2012). So, it is commonly the case that affluent nations, due to structural changes in their economies and the resource demands of economic development, have lower energy consumption and pollution emissions per dollar of GDP, while also having larger total consumption and emissions (Jorgenson and Clark 2012; Roberts and Grimes 1997; York, Rosa, and Dietz 2004).

The Jevons association is also common on other scales and in other contexts. For example, Grant et al. (2014) have shown that at the power plant level in the United States high levels of thermal efficiency are associated with high levels of fuel use. Gómez and Dionisio Pérez-Blanco (2014) demonstrate that implementing more efficient irrigation devices in agriculture worldwide results in increased demand for water in several irrigation networks, a result consistent with what Ward and Pulido-Velazquez (2008) found in the Upper Rio Grande Basin of North America. In Sweden, Brännlund, Ghalwash, and Nordström (2007) found that at the household level increases in energy efficiency increase carbon emissions. Similarly, Lin and Liu (2015) found that China's energy-efficient residential buildings only slightly reduce energy consumption in urban areas and increase total energy consumption in rural areas. Also, Wang, Zhou, and Zhou (2012) found that in China, increases in energy efficiency from passenger transport by urban households produce a rebound of 96%, which almost completely offsets any efficiency gains.

As these examples demonstrate, the positive association between efficiency and total resource use that lies at the heart of the Jevons association is a common phenomenon. Note that the aforementioned research finds that the Jevons association is often a result of multiple processes, not simply the cost mechanisms focused on in the economic literature on the rebound effect. All of the Jevons associations mentioned earlier, as well as the finding by Wang et al. (2012) of a high rebound that did not quite exceed 100%, were found to be, at least in part, a result of increased efficiency leading to consumption hikes in different sectors than where the efficiency improved. Jevons associations are often multifaceted phenomena, and appear to occur from more than just the direct effects on pricing, where indirect effects occur due to a spillover into consumption in other areas.

Importantly, the characterization of the Jevons association as paradoxical is not a claim that this association cannot be explained, but, to the contrary, it identifies something that needs to be explained. Noting the paradox is not a denial that anything can be done to change this association or an assertion that improving efficiency is always and necessarily bad for resource conservation, but it does suggest that more caution is needed in focusing on efficiency as a solution to our environmental problems. The fact of the association, even without making any assumption that the connection is causal, has two clear implications. First, it suggests that efficiency in and of itself is not a good indicator of good environmental performance of nations, power plants, households, etc., since in fact often the most efficient cases are the heaviest users of resources. When looking at nations or businesses, for example, efficiency is better understood as an indicator of *economic* performance, since it suggests more money is made per unit of resource consumed, than an indicator of *environmental/ecological* performance. Absolute resource consumption (or waste production) is the indicator of environmental performance that really matters, not efficiency. Second, the association suggests that even if efficiency does help reduce resource use, it is far from sufficient to lead to absolute reductions in resource consumption, and therefore efficiency should not be the singular or even primary focus of conservation efforts.

Efficiency and path dependency

It has been recognized for some time that the development and deployment of various technologies can set societies on particular paths of development that are difficult to deviate from once started on due to the momentum of previous technological decisions. In this vein, technological developments aimed at improving efficiency can potentially set societies on pathways that lead to the expansion of production and consumption, and thereby lead to greater resource consumption. There are two main ways in which path dependencies can be established. First, investment in technological infrastructure systems (such as road and car infrastructure) entails large sunk costs, and these investments are lost if the system is changed. Therefore, switching to alternative technologies can be costly since it would entail abandoning older systems that have already been paid for in favour of building new types of infrastructure. Efficiency improvements, such as in the fuel efficiency of cars (an example we take up in more detail), can serve to maintain societies on a particular development path (roads, suburban sprawl) by reducing immediate costs of the existing system, therefore preventing or delaying switching to other potentially less resource-intensive paths with high start up costs (Ayers and van den Bergh 2005; Greening, Greene, and Difiglio 2000; Polimeni et al. 2008). Second, focusing on efficiency can affect the type and amount of societal investment in technological development, which can spur a variety of innovations that alter production, consumption, and distribution systems. Although the trajectory set by technological innovation need not lead to more resource use, it can expand the potential for growth in production and consumption, which may lead to higher levels of resource use, undermining conservation (Ayers and van den Bergh 2005; Greening, Greene, and Difiglio 2000; Polimeni et al. 2008).

As mentioned earlier, there is a long tradition of political-economic theorizing and analysis, much of it in the Marxian tradition, focusing on macro-levels (e.g., cities, states, nations, and the global economy) that establish clear reasons why efficiency through its connection with growth dynamics and developmental pathways may lead to rising resource use. Although usually not explicitly making the distinction between the aforementioned two ways that the development of efficiency can affect development pathways, political-economic theorizing in environmental sociology typically has one or both of these routes implicit in its understanding of technology and the dynamics of growth. Bunker (1996) points out that, since even before the rise of industrial capitalism, efficiency has been a strategy for reducing production costs, not conserving resources, and has been associated with growing production and consumption since it helps generate profits that can be invested in the expansion of resource exploitation. Similarly, Schnaiberg (1980) argues that modern economies, particularly capitalist ones, are centred on seeking profits, not conserving resources. As noted in an earlier section, Schnaiberg and others argue improving efficiency works synergistically with expanding the exploitation of natural resources to generate profits. Therefore, this perspective suggests that efficiency is part of a developmental strategy, although not the driving force behind it, that leads to more and not less resource use. This type of growth dynamic has been observed not only at the international (Bunker 1996) and national levels (Schnaiberg 1980), but also at the city level (Molotch 1976).

Along these lines of argument, Zehner (2012) has noted that improving efficiency helps perpetuate resource-intensive practices, like car-centric transportation systems, and thereby serves to entrench high-energy lifestyles by undermining efforts to make major structural changes to societies that have the potential to dramatically reduce energy consumption. This suggests that improving efficiency contributes to maintaining a developmental pathway that is inimical to resource conservation. This is consistent with Jevons's (1865; Clark and Foster 2001) original argument about why greater efficiency in steam engines led to greater coal use – i.e., because efficiency made steam engines more cost-effective and more practical for use by industry and, therefore, more desirable to invest in. The improvements in efficiency, therefore, set societies, driven by profit-seeking industrialists, on a path of intensifying industrial development, where production processes became more and more efficient but demanded ever greater quantities of coal. It is important to recognize that this line of reasoning suggests that there is not only the indirect route by which efficiency stimulates consumption that is typically considered by scholars – i.e., money saved by resource efficiency can be spent on other goods and services that require the same resources to produce (Gillingham et al. 2013), but also a more indirect, but potentially much more powerful, route, along the lines of what Greening, Greene, and Difiglio (2000) call 'transformational effects,' by which energy efficiency helps to establish, maintain, and spur growth dynamics that are resource dependent.

A thought experiment can illustrate these types of processes and help conceptualize how energy efficiency can lead to more energy consumption. Consider two hypothetical worlds, similar to our own, but where there is stark disparity in the fuel efficiency of cars. In one world, all cars are extremely fuel efficient, being able to travel 50 kilometres on one litre of petrol. In the other world, all cars are extremely inefficient, requiring 50 litres of petrol to travel one kilometre. Therefore, cars in the efficient world are 2500 times more fuel-efficient than cars in the inefficient world. Likewise, other transportation technologies dependent on industrial age fuels, such as trains and planes, would have similar disparities in efficiency across the two hypothetical worlds. The key question in this thought experiment is, *in which world would fuel consumption be higher?*

Although it might at first seem that there should obviously be much less fuel used in the world with highly efficient cars, one must consider how structural development and individual behaviour would be different in the low-efficiency world. In the world where it takes 50 litres of petrol to travel one kilometre, it is likely that hardly anyone would ever drive. For one thing, it would be hard to fashion a car with a large enough fuel tank to travel very far. Other than this, it would be extremely expensive, even if fuel costs were much lower (as they assumedly would be, due to low demand), to drive even a few kilometres since so much fuel would be needed. In such a world, it would be far more practical and far less expensive to walk or bike than to drive. Perhaps more importantly, beyond the effect on individual behaviour, in a world where cars were extremely inefficient, infrastructure would have developed very differently than it has in our world.

In the low-efficiency world, it is possible that there would be no sprawling suburbs, innumerable roads, and expectations that people travel far for work, entertainment, or shopping. In the world with high fuel efficiency, there would likely be very little constraint on driving, so that the infrastructure, much like in our own world but more so, would be designed around cars and innovation would be directed to further develop car-centric technologies. Thus, we suggest that it is quite possible that there would be less fuel consumed in the low fuel-efficiency world than in the high fuel-efficiency world.

Of course, we only outline one potential scenario for how the low- and high-efficiency worlds would turn out, and in alternative scenarios, one can imagine the high-efficiency world being the one with lower fuel consumption. This thought experiment suggests that it is not efficiency itself per se that inhibits resource conservation, but rather the types of technologies that higher efficiency enables to become established – as in this example where efficiency may play a role in enabling car-centric infrastructure and innovation. Of course, improvements in efficiency, alternatively, could lead to more environmentally beneficial technologies taking hold, so the effect of efficiency on resource consumption depends on the particular context. Additionally, concerted efforts, such as through appropriate policy, could change which technologies take hold, making it so that efficiency is more frequently connected with resource conservation. We present this thought experiment to show that there are plausible routes by which high efficiency can lead to more resource consumption, not to suggest that high efficiency invariably or inevitably leads to more consumption. However, this thought experiment does suggest that the high levels of car use and fuel consumption in our world, at least in some sense, may be due in part to the *efficiency* rather than the inefficiency of our technologies.

We do not suggest that this is by any means the only type of process that leads to the rebound/Jevons association, or that it is always and everywhere a dominant force. However, we do contend that this type of process has been common in the modern era. We present results based on an analysis of time-series data for the majority of nations in the world which show that the pattern of change in consumption, emissions, and efficiency is consistent with the path dependency explanation we offer here.

Analysis

We have developed a model – focusing on energy use, electricity consumption, and CO_2 emissions – to assess the hypothesis we assumed earlier, which is subtler than the typical framing of questions about how energy efficiency affects overall energy consumption. The major limitation to assessing the effects of macroeconomic energy efficiency on energy consumption is that efficiency at the national level is typically defined as GDP/energy consumption (or electricity consumption, or CO_2 emissions, or another measure of resource use or pollution emissions). In a model where energy consumption is the dependent variable and GDP is used as an independent variable, including efficiency makes the model tautological, since, based on its mathematical definition, efficiency combined with GDP completely, but uninformatively, explains energy consumption, so that no meaningful hypothesis about efficiency is actually being tested.

The nuanced model that we developed overcomes this problem by asking how efficiency affects overall consumption in a somewhat different, and theoretically more interesting, way. We question how does the level of energy efficiency (or electricity efficiency or carbon efficiency) of a national economy at any particular point in time affect the *growth rate* of energy use (or electricity consumption, or carbon emissions). This specification is not tautological and more directly addresses the political economic conceptualization we outlined earlier, where efficiency is theorized to affect the development dynamics of economies. By definition, *all else being equal*, more energy-efficient economies consume less energy. However, efficiency may shape how economies use energy as they develop, where energy-using technologies are more likely to remain entrenched in efficient economies and, therefore, highly efficient economies may experience higher rates of growth in energy use, electricity consumption, and carbon emissions than less-efficient economies.

Specifically, we use a differenced (change) model, where the dependent variables and the independent variables indicate change over time, with the one exception being efficiency, which is the absolute efficiency at the start of each time period. We examine five-year periods to allow for sufficient time for effects to unfold. We use a random-effects generalized least squares (GLS) model, controlling for AR(1) disturbances, with time dummies to control for period effects, including all nations for which there are sufficient data from the World Bank (2014) for 1960–2010. There are 11 periods of change in this time span (1960–1965, 1965–1970, etc.), and the level of efficiency is for the starting time of each period (1960, 1965, etc.). We include a suite of control variables that have been established in the research literature to be the key factors influencing energy-related variables. All variables are in natural logarithmic form before differencing, making these elasticity models. It is important to recognize that using a random-effects model with differenced data has the same benefits of using a fixed-effects model with undifferenced data, since both types of models control for temporally invariant factors that differ across nations, such as major geographic features (e.g., whether a nation is landlocked or surrounded by an ocean, its latitude, etc.). For our purposes, using the differenced data approach is necessary so that we can assess the connection between the point estimate for efficiency and the growth rate of energy use, electricity consumption, and carbon emissions. Table 2 presents summary statistics and explanations of all of the variables included in the models. Note that for GDP per capita, we also include a quadratic term (the difference in the square of the logarithm) to allow for a potentially non-linear relationship between GDP per capita and any of the dependent variables. All data are from the World Bank (2014).

Table 2. Summary statistics for variables in analysis.

Variable[a]	Mean	Standard Deviation
Δ Energy use, per capita[b]	.062	.191
Δ Electricity cons., p.c.[c]	.165	.227
Δ CO_2 emissions, p.c.[d]	.104	.356
Energy use efficiency[e]	14.808	.853
Electricity efficiency[e]	1.128	.877
CO_2 efficiency[e]	14.410	.859
Δ GDP per capita[f]	.105	.169
Δ Dependency ratio[g]	−.045	.070
Δ Urbanization[h]	.059	.076
Δ Manufacturing[i]	−.020	.307

Notes: Since the sample varies across models, the observations used here to calculate the mean and standard deviation vary across the variables. For energy use per capita, electricity consumption per capita, and CO_2 emissions per capita as well as the efficiency variables for each of these, the summary statistics are for only the observations included in each respective model (see Table 3). For the other variables, the summary statistics are for the observations in the model with the largest N (CO_2 emissions, N = 925).

[a]All variables, except the efficiency measures, are the change in the natural logarithm of the original variable over 5-year periods. To interpret the values in substantive terms, multiply the values by 100, which yields the approximate percentage change in the variable over a 5-year period (e.g., the value of .105 for the mean of GDP per capita indicates that the average change for 5-year periods across nations was approximately 10.5%, which corresponds with an annualized growth rate of approximately 2%). The values for the efficiency variables are the natural logarithm of the point estimates at the start of each 5-year period and, therefore, cannot be interpreted in the same way (i.e., as percentage growth rates) as the other variables.

[b]A measure of 'primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport' (World Bank 2014) measured in kilograms of oil equivalent.

[c]Per capita electricity consumption from all sources measured in kilowatt hours.

[d]Carbon dioxide emissions from industrial sources measured in metric tons.

[e]Each efficiency variable is GDP per capita divided by the per capita value of energy use, electricity consumption, and CO_2 emissions respectively.

[f]Measured in inflation adjusted, year 2005, US$.

[g]The age dependency ratio is the ratio of people under 15 years of age and over 64 years of age to those 15–64 years of age.

[h]The percentage of the population living in urban areas.

[i]The percentage of GDP from the manufacturing sector.

For all three dependent variables, growth in GDP per capita stands out as a key force (see Table 3). The quadratic term is significant and negative in all three models, meaning that the effect of GDP per capita attenuates at high values. However, it does not lead to a turning point within reach of most nations in the foreseeable future. Change in the manufacturing sector of the economy (economic output as percentage of total GDP) also has a significant positive effect on all three dependent variables. Urbanization (percentage of the population living in urban areas) has a significant effect on only energy use, and the age dependency ratio (the ratio of people under 15 years of age and over 64 years of age to those 15–64 years of age) has a significant effect on only CO_2 emissions.

Most importantly for the focus of this analysis, the level of efficiency has a positive effect on growth of all three dependent variables. This means that the higher the level of efficiency in a nation, the faster energy use, electricity consumption, and CO_2 emissions grow over time, suggesting that efficiency, ironically, may serve to entrench high-energy lifestyles, processes, and technologies and/or lead to changes in investment that lead to new paths of innovation that contribute to expanding production and consumption. Although there are various possible explanations for these findings, they are clearly consistent with the political-economic theorization we explained earlier, suggesting that efforts to improve efficiency are part of a path-dependent development process that serves to continually expand production and consumption.

The consistent finding that the level of efficiency is connected with growth in energy use, electricity consumption, and CO_2 emissions is robust in the face of a variety of statistical issues. First, we have estimated the same models with a fixed-effects model of the differenced data, which makes a second-order correction for temporality invariant rates of change that differ across nations, and get substantively the same results as we obtained in the models reported here for all three dependent variables. Second, we have also estimated the models using robust standard errors which adjust for residuals clustering by nation and we get the same substantive results in all three models. Third, we have estimated the models dropping all observations where the efficiency level is more than two standard deviations from the overall mean, which controls for ceiling and floor effects by eliminating instances when a nation is near a potential limit. Once again, these models produced substantively the same results for all three dependent variables. Fourth, we find no evidence that outliers in residuals drive our results. The residuals for the energy use and electricity models appear to be approximately normally distributed and the residuals for CO_2 emissions are also approximately normally distributed with the exception of two distinct outliers. Estimating the models dropping those two outliers yields substantively the

Table 3. Random-effects generalized least squares panel regression elasticity models of factors influencing change in energy use per capita, electricity consumption per capita, and CO_2 emissions per capita, 1960–2010.

	Δ Energy use p.c.	Δ Elec. cons. p.c.	Δ CO_2 emissions p.c.
	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)
Efficiency	.092*** (.010)	.111*** (.011)	.221*** (.017)
Δ GDP per capita	1.234*** (.189)	1.243*** (.222)	1.327*** (.297)
Δ (GDP p.c.)^2	−.044*** (.012)	−.049** (.014)	−.041* (.019)
Δ Dependency ratio	−.143 (.094)	−.189 (.114)	−.438* (.177)
Δ Urbanization	.297* (.133)	.124 (.165)	.355 (.187)
Δ Manufacturing	.064** (.023)	.088** (.028)	.076* (.032)
R^2 (overall)	.453	.435	.255
N	602/122	594/121	925/168

Notes: *** $p < .001$, **$p < .01$, *$p < .05$ (two-tailed tests)
Data are for 5-year intervals. The models include period dummy variables that are not shown. The models use the Prais-Winsten correction for first-order autocorrelation. The efficiency variable is in natural logarithmic form. The other independent variables and the dependent variables are the change in the natural logarithm of the factor.

same results. Additionally, we estimated the models dropping all observations where the residual was more than two standard deviations from the mean, and in all three models we obtained substantively the same results, providing further evidence that our findings are not the results of a few influential observations.

This analysis adds an important piece to our understanding of the connections between efficiency and overall resource use, in that it demonstrates how efficiency may not only have immediate effects on how resources are used, but additionally may be connected with developmental pathways. This is a more indirect effect than other indirect effects recognized in the literature (e.g., Gillingham et al. 2013), but it is a potentially much more consequential one. It is important to acknowledge that these results do not definitively establish the political-economic explanation about developmental pathways that we present here. The higher growth in energy/electricity consumption and CO_2 emissions in more efficient nations could also be due to greater technological and institutional capacities in those nations that allow for more growth. If this is the case, it suggests that efficiency is associated with such capacities, but is not necessarily the cause of them. We have, of course, controlled for economic growth and growth in some other factors, but there still could be other technological or institutional forces our models may have missed. The technological/institutional explanation and the political-economic explanation, of course, are not mutually exclusive, and both phenomena (or neither) could be happening. The main point we draw from this analysis is that we should not assume that efficiency is necessarily a sufficient solution to resource consumption problems, and that it is at least plausible that, in some contexts, efficiency may, counter-intuitively, contribute to growth in resource consumption.

Conclusion

One of our central aims here has been to clarify some of the key issues in debates about the connections between efficiency and total resource consumption in the literatures on the rebound effect and the Jevons paradox. In particular, we argue that it is important to recognize the distinction between the association that characterizes the Jevons paradox (i.e., a positive correlation between efficiency and resource consumption) and the causal relationships that underlie this association. As we show, the Jevons association is quite common, although, of course, far from universal, at multiple scales and in various contexts. The reasons for this association are likely multiple and vary across time, place, and the specific type of efficiency examined. The simple fact of the association suggests that it may be inappropriate to use efficiency as an indicator of good environmental performance, since it is often the case that nations, power plants, households, and other units that are highly efficient use a greater absolute quantity of resources, not a lesser amount.

However, the fact of the frequent positive correlation between efficiency and resource use does not necessarily mean that greater efficiency causes greater resource consumption. Resource consumption may rise in spite of or coincidently with rising efficiency, rather than because of it. Nonetheless, there are also situations where efficiency leads to expanding resource use, through direct and/or indirect causal processes. Here, drawing on political economic theory, we identify one indirect process where efficiency sets developmental pathways that over time lead to rising resource consumption. We demonstrate that the empirical pattern of change in energy use, electricity consumption, and CO_2 emissions across many nations over the past five decades is consistent with this theorized process.

It is important to emphasize that there is no necessary reason that the Jevons/rebound effect must occur. In principle, policies can be designed to ensure that efficiency gains are converted into lower resource consumption rather than higher levels of production. For example, increasing taxes on natural resources would help to ensure that efficiency is converted into conservation rather than simply more production and consumption. This is analogous to how rising labour productivity can be converted into higher wages for workers, rather than simply larger profits for corporations, by minimum wage laws, union agreements, and so forth. Of course, this observation highlights that resource conservation requires not simply technology development, but political struggle as well, since the acts necessary to prevent the expansion of resource consumption, like those needed to improve the conditions of workers, may face resistance from some powerful actors. A key challenge for sociologists is to further develop our understanding of how social, political, and economic changes can be brought about that can facilitate addressing environmental problems.

Our conceptual clarifications, along with our explication of theory and our empirical analyses, show that rebounds and the Jevons paradox need to be thought of in subtle ways, recognizing that they do not represent one phenomenon, but rather a variety of processes. Understanding the particular processes occurring in any one situation is an important task for scholars, as is aiming to identify what circumstances are conducive to having rises in efficiency convert to reductions rather than increases in resource consumption.

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No potential conflict of interest was reported by the authors.

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