

Multi-layered Jevons Effects, Socioeconomic Virtualization, and the Limits of Efficiency-Led Sustainability

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Abstract: Technological efficiency improvements are most often accepted as the central pathway toward environmental sustainability. However, rebound and backfire effects suggest that efficiency gains may, under certain conditions, increase, and not decrease aggregate resource use. This paper contributes to this debate by proposing a conceptual and formal framework that links efficiency-driven rebound effects to long-term technological development through a multi-layered mechanism. We introduce the notion of multi-layered Jevons effects to describe how successive rounds of efficiency improvements can cumulatively amplify resource throughput via cost reductions, price adjustments, and output expansion. To formalize this mechanism, we develop a stylized partial-equilibrium model with energy-augmenting technological change, demand responsiveness, and incomplete pass-through. In it, demand elasticities, cost shares, and technological effectiveness play the crucial roles. The model also derives explicit conditions under which efficiency improvements lead to backfire. Beyond the sphere of economy, we advance the concept of socioeconomic virtualization, defined as the increasing cognitive and institutional distance between final users and the material–energetic processes underlying production and consumption. We argue that virtualization can systematically shift key behavioural and market parameters—such as perceived marginal costs and demand responsiveness—in ways that increase the likelihood of rebound-dominated outcomes. We lack a universal proof of technological unsustainability. This paper is rather intended as a perspective treatise to identify plausible mechanisms, parameter regions, and testable hypotheses. The analysis suggests that efficiency-oriented sustainability strategies will unlikely deliver absolute reductions in resource use. This calls attention to the necessity of complementary binding constraints. Finally, we outline a research agenda for empirically investigating the interaction between technological efficiency, rebound effects, and socioeconomic virtualization.

Keywords: rebound effects; Jevons paradox; energy efficiency; socioeconomic virtualization; sustainability policy

1 Introduction

Technological progress is generally held as a primary driver of economic development and human well-being; from early agricultural innovations to successive industrial revolutions, and contemporary digital technologies [1-5]. Improvements in technical efficiency have historically enabled societies to produce more goods and services with fewer inputs. This has led to expectations that continued innovation can even reconcile economic growth with environmental sustainability. This expectation underlies many policy strategies which emphasize improvements in efficiency, substitution of technologies, and the innovation-led “green growth” as central solutions to ecological crises [6-9].

However, this assumption, i.e. that efficiency gains translate straightforwardly into absolute reductions in resource use, has been challenged by numerous authors. Beginning with William Stanley Jevons’ nineteenth-century observations on coal consumption [10], and later formalized in the Khazzoom-Brookes postulate [11-13], scholars have repeatedly shown that efficiency improvements can lead to rebound effects, whereby lower effective costs eventually result in increased demand. This offsets some or all or even more of the expected resource savings [14-17]. Empirical and modelling studies have documented those effects across energy services, industrial sectors, and entire economies. Magnitudes of these effects range from partial rebound to full backfire, depending on behavioural, technological, and market conditions [18-22].

Rebound effects are not limited to direct, end-use responses. They may propagate through indirect, economy-wide, and structural channels [15, 20, 21, 23]. There begins the interpretation of rebound as a broader mechanism; moreover, this is particularly relevant when efficiency is improved in economy wide core inputs, like energy. Price changes are transmitted through supply chains up to final good markets [24-26]. The relationship between efficiency, prices, output expansion, and aggregate resource use depends on demand elasticities, cost shares, and the degree of pass-through from production costs to consumer prices [24-26].

Yet macroeconomic trends suggest that large-scale effective results always tend towards the ‘unsustainable’ direction, i.e. system complexity favours the dominance of the rebound effect on the scales of whole economies. These trends form the subject of debates on GDP-ecological footprint decoupling. This is nothing else but the lack of sustained reduction in environmental cost alongside economic growth. Relative or territorial decoupling have been observed in specific countries or periods, but general decoupling of GDP from material and energy footprint is limited, temporary, or contingent on structural shifts, and outsourcing through trade [7, 8, 23, 27-29, 33, 34], i.e. ecological footprint embodied in traded goods. Efficiency-led strategies have thus systemic limitations in delivering long-term sustainability. Complementary constraints on throughput shall be in place to achieve this.

Sociocultural dimensions of resource use also interact with technological change. Technological development often increases the mental distance between human decision making and the physical processes underlying production and consumption [32-35]. This is the long-term anthropological and sociological aspect. Technologies become more complex and more sophisticated using multi-layered interfaces, and in parallel, users and consumers lose direct sensory and cognitive feedback about resource extraction, energy use, and environmental impact [36-45]. We refer to this as *socioeconomic virtualization*. This is not only digitalization in a narrow sense, it includes a broader historical trend toward mediated, opaque, and abstracted interactions with material reality. It has begun in prehistorical ages already [1-4, 32, 33, 36, 38].

Virtualization systematically amplifies rebound mechanisms when it alters behavioural and market parameters. Reduced salience of resource use, weaker feedback signals, and greater informational asymmetries increase the response of demand to changes in price, for example. Perceived marginal resource costs also weaken. This all facilitates a higher pass-through of efficiency gains into consumption expansion [46-48]. Therefore, improvements in technological efficiency and virtualization co-evolve with resource hunger. These effects reinforce one another over successive waves of innovation.

This background given, the present paper puts out three contributions. First, we introduce the concept of *multi-layered Jevons effects* to describe how successive rounds of efficiency improvements cumulatively increases aggregate resource throughput via repeated cost reductions, price adjustments, and output expansion. Second, we provide a stylized formal framework that derives the basics of explicit conditions under which rebound in energy-augmenting technological changes lead to backfire. This is based on demand elasticities, cost shares, technological effectiveness, and price pass-through. Third, we propose socioeconomic virtualization as a complementary lens for understanding why modern economies systematically operate in parameter regions where rebound dominates.

There may be no universal proof that technological development is inherently unsustainable. This paper is, however, intended as a perspective contribution that identifies plausible mechanisms, bounded claims, and later, testable hypotheses about the widely perceived unsustainable outcomes. We integrate insights from rebound economics, production theory, and sociocultural analysis, in order to outline a further research agenda. It should be empirically investigated how efficiency improvements, market responses, and virtualization jointly shape long-term sustainability outcomes (generally unfavourable so far). It is also an important question under what – possibly widespread – conditions efficiency-oriented policies do require binding policy constraints to achieve absolute reductions in resource use.

2 Review: Jevons Effects and Socioeconomic Virtualization

2.1 The Jevons Effect and Rebound Mechanisms

The Jevons paradox was articulated originally by William Stanley Jevons, in the context of nineteenth-century coal use in England. It describes the counter-intuitive observation that improvements in resource efficiency leads to increased, not decreased, total consumption of that resource [10]. It started as a historical curiosity, but subsequent theoretical and empirical work has demonstrated that this is a more general economic mechanism. Efficiency improvements reduce the effective cost of resource-intensive services, which in turn, stimulates demand and expanding output [14, 16] (this is why we prefer the notation ‘Jevons effect’ over the exceptionality-oriented ‘Jevons paradox’ [49, 50]).

In the modern literature, this is discussed under the broader concept of rebound effect. Direct rebound refers to increased consumption of the same service whose efficiency has improved. This is a normal response of consumers to lower prices [14, 22]. Indirect rebound in compound situations (whole economies) captures additional resource use arising from re-spending cost savings on other goods and services [19, 46]. Economy-wide rebound on large, complex scales encompasses macroeconomic adjustments, including price changes, structural shifts, and income effects. These propagate efficiency gains throughout an economy [15, 20, 21, 23]. On each scale, when the combined magnitude of these effects exceeds the initial efficiency improvement, total resource use increases. This situation is often referred to as backfire [11-13].

Crucially, the magnitude of rebound and thus, the likelihood of backfire depend on well-defined economic parameters. This is not a paradoxical or anomalous behaviour. Demand elasticities, substitution possibilities among production inputs, cost shares, and pass-through from production costs to output prices govern it [18, 19, 24, 26]. Jevons-type effects are not a kind of exception to otherwise benign efficiency improvements. They necessarily emerge under plausible and empirically observed conditions.

In the context of general technological (cultural) context, efficiency improvements occur repeatedly over time and across sectors. Successive rounds of innovation generates cumulative cost reductions, stimulate new applications, as well as expand markets. Recent sustainability literature analyzes the ways that amplify resource throughput beyond what results from isolated efficiency gains [15, 20]. This temporal and structural accumulation motivates the notion of *multi-layered* rebound or Jevons effects. The long-run impact of technological progress differs qualitatively from its short-run, partial-equilibrium effects.

2.2 Technological Development and Socioeconomic Virtualization

Anthropology, sociology, science and technology literature have also examined how technological development reshapes human relationship with the physical world [32-35]. Beginning with early tools and agricultural practices, and up to industrial machinery and contemporary digital systems, technologies as multiple inserted layers of interaction have progressively obscured the connection between humans and the physical processes that sustain production and consumption [1-4, 36, 38].

We use the term *socioeconomic virtualization* to denote this long-term tendency toward increasing mediation, abstraction, and opacity in resource use. Once again, virtualization is not limited to digital or information technologies in a narrow sense. It encompasses a broader historical process: technological layers separate decision-makers and end users from direct sensory, cognitive, and institutional feedback about resource extraction, energy flows, and environmental impact [37-45]. Examples are agriculture itself, then mechanized agriculture, and further, automated industrial production, up to globalized supply chains and algorithmically mediated consumption.

Reduced visibility of material and energetic inputs weaken the feedback mechanisms that would otherwise possibly constrain consumption. Informational asymmetries and complex interfaces lower the perceived marginal costs of additional use [46, 47]. At the same time, moreover, technological mediation facilitates the diffusion of efficiency gains through markets. This effectively increases the likelihood that cost reductions end up in lower prices and expanded demand [24-26].

As a crucial consequence, virtualization is not merely a cultural backdrop to economic processes. It interacts directly with the parameters that govern rebound effects. By shaping preferences, perceptions, and institutional settings, virtualization has an influence on demand elasticities, substitution behaviour, and price responsiveness, etc. Thereby it affects in a systematic way whether and how efficiency improvements result in net savings or increased resource use. Rebound effects and virtualization are not independent phenomena, but potentially co-evolving – economic and sociocultural – aspects of technological development.

2.3 From Isolated Rebound to Multi-layered Jevons Effects

The concept of *multi-layered Jevons effects* is meant to collect repeated instances of single Jevons effects settled down on top of each other in socioeconomic systems. As a consequence, this turns technological efficiency into higher aggregate throughput. Technological evolution, improvements in efficiency reduce costs at multiple points in production and consumption chains. In parallel, virtualization

attenuates feedback and amplifies behavioural and market responses. This shifts economies into effective parameter regions where rebound-dominated outcomes are likely.

This perspective does not principally imply that efficiency improvements are necessarily always counterproductive. Rather, it shows the importance of identifying the possibly abundant conditions under which rebound effects accumulate across layers of technological change and interact with sociocultural dynamics. In the following section, we outline a stylized formal framework with which we try to capture these mechanisms in a transparent manner. We derive fundamental explicit conditions under which energy-augmenting technological change finally leads to rebound or even backfire effects. This framework is meant to be a basis when the multi-layered Jevons hypothesis is empirically tested; or furthermore, when the limits of efficiency-oriented sustainability strategies are to be assessed.

3 Methodology: a Stylized Framework for Efficiency, Rebound, and Backfire

Here, we formalize the economic mechanism underlying multi-layered Jevons effects. To this end, we consider a stylized partial-equilibrium framework with a representative production sector. Output Q is produced using two inputs: an energy or resource input E , representing natural or environmental resources, and a composite input K , capturing all other production factors. Production technology is assumed to have constant returns to scale, and it has a constant-elasticity-of-substitution (CES) production function

$$Q = Q_0 [\alpha (AE)^\rho + (1 - \alpha) K^\rho]^{\frac{1}{\rho}},$$

where $A > 0$ denotes the energy-augmenting efficiency parameter. $\alpha \in (0,1)$ is a distribution parameter, and ρ (where $\rho \leq 1, \rho \neq 0$) determines the elasticity of substitution. An increase in A corresponds to an efficiency improvement that raises the productivity of the energy input. This does not directly affect the productivity of the other (composite) input K .

Firms are assumed to minimize production costs for a given output level, taking input prices p_E and p_K as given constants (note, however, that temporarily reduced use of E lowers its price, making it more attractive to use, and thus further contributing to rebound effects). Under standard regularity conditions, the unit cost function associated with the above CES technology is

$$c(p_E, p_K, A) = \frac{1}{Q_0} \left[\alpha^\sigma \left(\frac{p_E}{A} \right)^{1-\sigma} + (1 - \alpha)^\sigma p_K^{1-\sigma} \right]^{\frac{1}{1-\sigma}}.$$

Note that $\sigma = 1/(1 - \rho)$. This expression shows how energy-augmenting technological change affects production costs through reduced effective price of energy, p_E/A . Log-linearizing around an initial equilibrium yields an approximation when changes in efficiency are small:

$$\Delta \ln c \approx -s_E \Delta \ln A,$$

where $s_E = \frac{p_E \cdot E}{c \cdot Q} = \frac{\partial \ln c}{\partial \ln E}$ denotes the share of energy in total production costs at the cost-minimizing input combination. Thus far, this is the direct cost-reducing effect of efficiency improvements [18, 24, 51].

3.2 Price Adjustment, Pass-through, and Output Response

Next, we connect cost reductions to market outcomes. To this end, we introduce a reduced description of price adjustment. Let P be the output price, and then we assume that changes in unit production costs are being transmitted to output prices with a pass-through rate of $\mu \in (0,1]$:

$$\Delta \ln P \approx \mu \Delta \ln c.$$

The parameter μ embodies circumstances, like market structure, competitive conditions, and institutional features, etc. Those all affect how strongly cost changes get reflected in prices [51, 52]. Perfect competition with elastic supply results in μ close to one, however, empirical evidence suggests substantial variations of it across different sectors and contexts (e.g. [52-55]).

On the demand side, we default to an isoelastic (w.r.t. price) final demand

$$Q(P) = B P^{-\varepsilon},$$

where $\varepsilon > 0$ is the (absolute value of) price elasticity of demand. Linearizing this yields

$$\Delta \ln Q = -\varepsilon \Delta \ln P.$$

Finally, we combine the cost and price relationships, and get

$$\Delta \ln Q \approx \varepsilon \mu s_E \Delta \ln A.$$

This expression summarizes the expansion of the output channel, which is emphasized in the rebound literature. Thus, improvements of efficiency reduce costs, then lower prices, and last, increase demand. The magnitude of the response is governed by demand elasticity, pass-through, and the weight of energy in production costs [14, 24, 43].

3.3 Aggregate Resource Use and the Backfire Condition

Total energy, or generally, resource use, is given by the product of output and unit input requirements, naturally:

$$E = e Q.$$

Here, e denotes the amount of energy, which is used per each unit of output, taken at the cost-minimizing input combination. By the supposed energy-augmenting technological change, efficiency improvements reduce energy requirements. We introduce ϑ as the effective rate with which the energy-augmenting technology change gets expressed in e through production:

$$\Delta \ln e \approx -\vartheta \Delta \ln A.$$

Note that this $\vartheta \in (0,1]$ and A in combination measure the extent of reductions in physical energy use per unit of output; A being on the input side, an effective ϑ being on the output side of production. Values of ϑ below unity reflect aggregate effects of technological details in volume production, organizational responses, other adjustments, etc. that attenuate primary efficiency gain [18, 19].

The change in total energy (resource) use in terms of efficiency change, as a result of all the intermediary effects discussed so far is

$$\Delta \ln E \approx (-\vartheta + \varepsilon \mu s_E) \Delta \ln A.$$

Rebound effect means that other effects attenuate ϑ , the primary effective resource reduction. Backfire occurs when the rebound term dominates, i.e.

$$\varepsilon \mu s_E > \vartheta.$$

The meaning of this result is that backfire is not a ‘paradox’ but a parameter-dependent outcome. High demand responsiveness, substantial pass-through, and large energy cost shares increase the likelihood that backfire occurs.

3.4 Iteration and the Logic of Multi-layered Jevons Effects

Technological development settles down into socioeconomic systems in successive waves, not as isolated improvements. Let A_t now denote the efficiency parameter in step t . Iterative application of the single-step result gives

$$\Delta \ln E_{\text{total}} = \sum_t \Delta \ln E_t \approx \sum_t (-\vartheta_t + \varepsilon_t \mu_t s_{E,t}) \Delta \ln A_t.$$

In each step, $\varepsilon_t \mu_t s_{E,t} > \vartheta_t$ is the backfire condition. Naturally, in multiple-step improvement chains, it is enough that backfire-type steps dominate the chain, and the probability of such improvement chains is effectively high if it can be shown that backfire is a frequent outcome of technological improvement steps. Note that this goes in connection with the socioeconomic context of virtualization, further increasing the likelihood of backfire-type steps. If e.g. demand elasticity or pass-

through rise over time—as suggested nearly as a “cultural necessity” by the literature on market expansion, globalization, and socioeconomic virtualization—, rebound-dominated long-term outcomes become more and more frequent [15,20,23], giving rise to an eventual general backfire effect in a wide spectrum of (usual) circumstances.

The framework presented here is meant to be basic and stylized. It is not a general equilibrium proof of inevitable backfire, nor does it account for all the possible indirect (up to macroeconomic or societal) rebound strengthening effects. Rather, it provides a transparent, rugged-down mechanism to identify the conditions under which efficiency improvements likely increase resource throughput. This is the motivation for empirical investigation and policy analysis that we propose in the subsequent sections.

4 Discussion and Policy Implications

4.1 Interpreting the Model Results

The stylized framework we have developed in Section 3 clarifies the conditions under which efficiency improvements fail to deliver effective reductions in resource use. This points to the possible contradiction between technological progress and sustainability, as the model highlights a tension between these two opposing forces: reductions in unit resource requirements, and expansion of output induced by lower costs and prices. The possibilities of net resource savings or increased throughput depend mainly on a small set of parameters. These are demand elasticity, cost pass-through, energy cost shares, and the overall production effectiveness with which technological improvements reduce physical input requirements.

Rebound and backfire should be thus understood as parameter-dependent outcomes; they are strictly not paradoxical anomalies. In economic environments characterized by high demand responsiveness, substantial pass-through, and significant energy or resource cost shares (note how much these may be structurally inherent to nowadays welfare economies), efficiency improvements are prone to lead to increased aggregate resource use. Conversely though, when demand is relatively inelastic, pass-through is limited, or efficiency gains translate directly into large reductions in unit input requirements, efficiency improvements generate net savings. This perspective aligns with empirical findings about heterogeneous rebound magnitudes across sectors, technologies, and institutional contexts [14, 18, 19-22] (the systematic ‘big picture’ remaining the important aspect, however).

The above heterogeneity does also cover seemingly conflicting results in rebound and decoupling literature. [7, 8, 14-23, 27-29, 34, 43-46] Observations of relative or temporary decoupling are not inconsistent with the existence of (widespread, or systematic) rebound effects. There can be periods or sectors in which the relevant parameters temporarily fall below the backfire threshold. Over longer time horizons or across successive waves of innovation, cumulative efficiency improvements seem to interact with evolving market and behavioural conditions in such ways that shift whole economies towards rebound-dominated (backfire-type) regimes.

4.2 Multi-layered Jevons Effects and Technological Trajectories

Our notion of *multi-layered Jevons effects* emphasizes the dynamic and cumulative, eventually dominant nature of efficiency-driven rebound. Its basis is that technological development rarely comes in isolated improvements. It unfolds through iterative innovations that affect multiple stages of production, distribution, and consumption at once. Even if each efficiency gain reduces costs locally, when such gains occur across layers and over time, their combined effect can significantly expand overall economic activity and then resource throughput.

Then, the critical issue in this setting is not whether a single efficiency improvement causes rebound, but the long-run trajectory of cumulative technological changes. The latter can be systematically in parameter regions, which is prone to backfire. Successive innovations can increase demand elasticities, they can facilitate higher pass-through, or maintain high resource cost shares. Thus, efficiency gains translate into even higher increments in aggregate resource use. This dynamic interpretation is consistent with the historical accounts of industrial development. That is, major efficiency breakthroughs have often coincided with rapid expansion of production and consumption—connected in turn to forward leaps in welfare [11-13].

This does not imply that technological innovation is necessarily wrong, undesirable or that efficiency improvements should be abandoned. This suggests that efficiency alone shall not be relied upon as the sufficient condition for sustainability. Complementary mechanisms shall be applied that explicitly or implicitly constrain total throughput. Efficiency gains shall be saved from expansion effects at multiple layers of economy.

4.3 Socioeconomic Virtualization as an Amplifying Mechanism

The concept of *socioeconomic virtualization* has been introduced in Section 2. It provides a tool for interpreting why modern economies systematically approach or cross the backfire threshold identified in the model. Technological systems become more complex and mediated; thus users and decision-makers experience reduced, indirect visibility of the material and energetic foundations of economic activity.

This attenuation of feedback alters preferences, perceptions, and institutional responses. This is in the background of, e.g. increasing demand responsiveness and weakening behavioural constraints on consumption.

As the important feedback for the economic framework, virtualization can be interpreted as an external (socioeconomic, even cultural) force that shifts key parameters over time. Reduced salience of resource use increases demand elasticities; complex supply chains and digital interfaces facilitate rapid diffusion of cost reductions and higher pass-through to final prices, etc. Organizational and technological adaptations also dampen efficiency gains as the source of reduction in unit resource requirements. Altogether, these effects move economies into parameter regions of rebound-dominated outcomes; even in the absence of explicit changes in efficiency due to technology or policy.

These links remain to be empirically established, yet, virtualization as a changing force on model parameters helps bridge the sociocultural analysis and the parallel economic modelling. It also suggests directions for future research. These include measurement of resource salience, informational opacity, and their relationships to consumption behaviour, institutional systems, market responses, etc.

4.4 Implications for Sustainability Policy

Our analysis presented here brings several implications for sustainability-oriented policy. First, policies that rely primarily on efficiency improvements will not likely achieve absolute reductions in resource use when the relevant economic (and behavioural) parameters keep the system near or beyond the backfire threshold. This limits the ability of efficiency-alone policies to deliver sustainability.

Second, our framework underscores the importance of policies that directly address total throughput. These are instruments such as resource caps, binding emission limits, quantity-based regulations, or sufficiently stringent pricing mechanisms. These are the policies which can alter the effective demand response and constrain expansion effects. These are policy tools which favourably change the contextual parameters for efficiency improvements [56-60]. Complete with them, efficiency gains become able to contribute to sustainability; e.g. by reducing the costs of meeting binding constraints instead of contributing to output expansion.

Third, the role of socioeconomic virtualization hints the relevance of informational and institutional (even culturally ‘soft’) interventions. Policies shall be in place that increase transparency of resource use, enhance feedback to consumers and firms, or reduce informational asymmetries. This shall then influence demand responsiveness and perceived costs, as a complement to traditional economic instruments. Such measures are not sufficient to substitute binding constraints, but they help moderate rebound effects on a ‘softer’ level, and thus they also support more efficient sustainability strategies.

Overall, technological efficiency should be understood as a *conditional and context-dependent* component of sustainability policy. Its effectiveness depends by far not only on technical details, but also on higher systematic levels, as market structures, behavioural responses, and all the broader socioeconomic, sociotechnical, and sociocultural environments in which efficiency gains are embedded.

5 Conclusions and Outlook

This paper is intended to examine the relationship between technological efficiency improvements and long-term sustainability. This is motivated by the persistent tension between mainstream expectations of “green growth” and, in contradiction, empirical evidence on rebound and backfire effects. Without a universal proof of technological unsustainability (the question still being open), our analysis is about integrating insights from rebound economics, production theory, and sociocultural analysis. We try to identify plausible mechanisms, combinations thereof, and conditions under which efficiency-oriented strategies fail to reduce system wise aggregate resource use. We treat two principal aspects of this question.

First, we introduce the concept of *multi-layered Jevons effects* to capture the cumulative nature of multiple rebound mechanisms present across successive waves of technological change, or successive layers of a production chain or another economical (sub-) system. We describe efficiency improvements in a stylized production and demand framework, and try to derive basic explicit conditions under which energy-augmenting (or other resource-augmenting) technological changes lead to rebound or backfire effects. The derivation is based on the roles of demand elasticity, cost pass-through, cost shares, and the overall effective reduction of physical input requirements. These results clarify that rebound and backfire are parameter-dependent outcomes, not paradoxical anomalies.

Second, we propose the introduction of the notion of *socioeconomic virtualization* as a complementary instrument in order to understand why modern economies seem to *systematically* approach or even cross the backfire threshold. This is the process which increases the cognitive, procedural, and institutional distances between scenes of decision making and the material-energetic (physical) foundations of production and consumption. Thus, virtualization shifts key behavioural and market parameters in ways that amplify economic expansion, leading to rebound, or even backfire effects. While this linkage is largely conceptual yet, our concept which frames virtualization in terms of its potential influence on model parameters may serve as a bridge between economic mechanisms and sociotechnical, socioeconomic, and sociocultural phenomena in a broader sense.

There are limitations of the present analysis which should be acknowledged. We have given a deliberately stylized, and partial-equilibrium formal framework, abstracting from general equilibrium feedback, distributional effects, as well as heterogeneity across different agents and sectors. Moreover, the concept of

socioeconomic virtualization has not yet been operationalized empirically, though suggested by historical observations. Its effects on demand responsiveness and market behaviour should be systematically tested yet. These limitations are not weaknesses of the argument, they rather define a scope of a research agenda for which this paper seeks to be the initialization.

Future research will be built on the proposal of this paper in several directions. E.g. empirical work should estimate the key parameters governing rebound and backfire in different situations, sectors and technological contexts. It should be also assessed how these parameters evolve over time. The development of measurable indicators of socioeconomic virtualization – such as resource salience, informational opacity, or supply-chain depth – also allows researchers to get a deeper insight into whether and how virtualization contributes to rebound or backfire effects. An extension of our framework to general equilibrium settings and a possible incorporation of institutional and policy constraints would further clarify under which conditions efficiency improvements are able to contribute to absolute and effective reductions in resource usage.

In conclusion, our analysis suggests that improvements to technological efficiency should be cautiously understood as conditional and context-dependent components of sustainability strategies. Efficiency plays a valuable role in reducing the costs of complying to environmental constraint rules, but it unlikely delivers absolute sustainability outcomes on its own, when expansion effects remain unconstrained. Furthermore, the recognition of the multi-layered nature of rebound mechanisms and the sociotechnical context in which efficiency gains are embedded is essential for designing realistic and efficient sustainability policies.

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7 References

- [1] Sanford, T. (2024) *Agricultural Revolution*. In: *A Whirlwind History of the Universe and Mankind: From the Big Bang to the Higgs Boson* (pp. 41-55) Singapore: Springer Nature Singapore. doi:10.1007/978-981-97-2674-5_5

- [2] Larsen, C. S. (2006) *The agricultural revolution as environmental catastrophe: Implications for health and lifestyle in the Holocene*. Quaternary International, 150(1), 12-20. doi:10.1016/j.quaint.2006.01.004
- [3] Sharma, Ashwani, and Bikram Jit Singh. *Evolution of industrial revolutions: A review*. International Journal of Innovative Technology and Exploring Engineering 9.11 (2020): 66-73. doi:10.35940/ijitee.I7144.0991120
- [4] Groumpos, Peter P. *A critical historical and scientific overview of all industrial revolutions*. IFAC-PapersOnLine 54.13 (2021): 464-471. doi:10.1016/j.ifacol.2021.10.492
- [5] Albritton Jonsson, F. (2012) *The industrial revolution in the Anthropocene*. The Journal of Modern History, 84(3), 679-696. doi:10.1086/666049
- [6] York, R., & McGee, J. A. (2016) *Understanding the Jevons paradox*. Environmental Sociology, 2(1), 77-87. doi:10.1080/23251042.2015.1106060
- [7] Dominik Wiedenhofer, Doris Virág, Gerald Kalt, Barbara Plank, Jan Streeck, Melanie Pichler, Andreas Mayer, Fridolin Krausmann, Paul Brockway, Anke Schaffartzik, Tomer Fishman, Daniel Hausknost, Bartholomäus Leon-Gruchalski, Tânia Sousa, Felix Creutzig and Helmut Haberl. *A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping*. 2020 Environ. Res. Lett. 15 063002 doi:10.1088/1748-9326/ab8429
- [8] Helmut Haberl, Dominik Wiedenhofer, Doris Virág, Gerald Kalt, Barbara Plank, Paul Brockway, Tomer Fishman, Daniel Hausknost, Fridolin Krausmann, Bartholomäus Leon-Gruchalski, Andreas Mayer, Melanie Pichler, Anke Schaffartzik, Tânia Sousa, Jan Streeck and Felix Creutzig. *A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights*. Environmental research letters, 15(6), 065003. doi:10.1088/1748-9326/ab842a
- [9] Huesemann, M. H. (2003) *The limits of technological solutions to sustainable development*. Clean technologies and environmental policy, 5, 21-34. doi:10.1007/s10098-002-0173-8
- [10] Jevons, William Stanley. *The coal question; an inquiry concerning the progress of the nation and the probable exhaustion of our coal-mines*. Macmillan, 1866
- [11] Khazzoom, J. D. (1980) *Economic implications of mandated efficiency in standards for household appliances*. The Energy Journal, 1(4), 21-40
- [12] Brookes, L. (1990) *The greenhouse effect: The fallacies in the energy efficiency solution*. Energy Policy, 18(2), 199–201. doi:10.1016/0301-4215(90)90079-T

-
- [13] Saunders, H. D. (1992) *The Khazzoom–Brookes postulate and neoclassical growth*. *The Energy Journal*, 13(4), 131-148
- [14] Sorrell, Steve. Jevons' Paradox revisited: *The evidence for backfire from improved energy efficiency*. *Energy policy* 37.4 (2009): 1456-1469. doi:10.1016/j.enpol.2008.12.003
- [15] Lange, S., Kern, F., Peuckert, J., & Santarius, T. (2021) *The Jevons paradox unravelled: A multi-level typology of rebound effects and mechanisms*. *Energy Research & Social Science*, 74, 101982. doi:10.1016/j.erss.2021.101982
- [16] Alcott, Blake. *Jevons' paradox*. *Ecological economics* 54.1 (2005): 9-21. doi:10.1016/j.ecolecon.2005.03.020
- [17] Amado, Nilton Bispo, and Ildo L. Sauer. *An ecological economic interpretation of the Jevons effect*. *Ecological complexity* 9 (2012): 2-9. doi:10.1016/j.ecocom.2011.10.003
- [18] Saunders, H. D. (2013) *Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts*. *Technological Forecasting and Social Change*, 80(7), 1317-1330. doi:10.1016/j.techfore.2012.12.007
- [19] Azevedo, I. M. L. (2014) *Consumer end-use energy efficiency and rebound effects*. *Annual Review of Environment and Resources*, 39, 393–418. doi:10.1146/annurev-environ-021913-153558
- [20] Brockway, P. E., Saunders, H., Heun, M. K., Foxon, T. J., Steinberger, J. K., Barrett, J. R., & Sorrell, S. (2017) *Energy rebound as a potential threat to a low-carbon future: Findings from a new exergy-based national-level rebound approach*. *Energies*, 10(1), 51. doi:10.3390/en10010051
- [21] Freire-González, J., & Vivanco, D. F. (2017) *Assessing the economy-wide rebound effect for household energy consumption in Europe*. *Energy Policy*, 101, 335–342. doi:10.1016/j.enpol.2016.11.027
- [22] Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009) *Empirical estimates of the direct rebound effect: A review*. *Energy Policy*, 37(4), 1356-1371. doi:10.1016/j.enpol.2008.11.026
- [23] Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Streeck, J., Pichler, M., Krausmann, F., Brockway, P., Schaffartzik, A., Fishman, T., Hausknost, D., Leon-Gruchalski, B., Sousa, T., Mayer, A., & Haberl, H. (2020) *A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part III: Economy-wide rebound and structural effects*. *Environmental Research Letters*, 15(6), 065004. doi:10.1088/1748-9326/ab842b
-

- [24] Borenstein, S. (2015) *A microeconomic framework for evaluating energy efficiency rebound and some implications*. The Energy Journal, 36(1), 1–21. doi:10.5547/01956574.36.1.1
- [25] Fabinger, M., & Weyl, E. G. (2016) *Pass-through as an economic tool*. Journal of Political Economy, 124(4), 899–946. doi:10.1086/686605
- [26] Ganapati, S., Shapiro, J. S., & Walker, R. (2020) *Energy cost pass-through in U.S. manufacturing: Estimates and implications for carbon taxes*. American Economic Journal: Applied Economics, 12(2), 303–342. doi:10.1257/app.20180115
- [27] Mattila, Tuomas. *Any sustainable decoupling in the Finnish economy? A comparison of the pathways and sensitivities of GDP and ecological footprint 2002-2005*. Ecological Indicators 16 (2012): 128-134. doi:10.1016/j.ecolind.2011.03.010
- [28] Akizu-Gardoki, O., Bueno, G., Wiedmann, T., Lopez-Guede, J. M., Arto, I., Hernandez, P., & Moran, D. (2018) *Decoupling between human development and energy consumption within footprint accounts*. Journal of Cleaner Production, 202, 1145-1157. doi:10.1016/j.jclepro.2018.08.235
- [29] Szigeti, Cecília, Gergely Tóth, and Dániel Róbert Szabó. *Decoupling–shifts in ecological footprint intensity of nations in the last decade*. Ecological Indicators 72 (2017): 111-117. doi:10.1016/j.ecolind.2016.07.034
- [30] Polimeni, J. M., Mayumi, K., Giampietro, M., & Alcott, B. (2008) *The Jevons paradox and the myth of resource efficiency improvements*. London: Earthscan
- [31] Radácsi L, Szigeti C. (2024) *The illusion of the holy grail of decoupling: Are there countries with relatively high SDGI and moderately low ecological footprint?* Environ Sustain Indic. 22, 100379. doi: 10.1016/j.indic.2024.100379
- [32] Ingold, Tim. *Eight themes in the anthropology of technology*. Social Analysis: The International Journal of Social and Cultural Practice 41.1 (1997): 106-138
- [33] Ruttan, Vernon W. *Cultural endowments and economic development: what can we learn from anthropology?* Economic Development and Cultural Change 36.S3 (1988): S247-S271. doi:10.1086/edcc.36.s3.1566545
- [34] Gray, Chris Hables, and Mark Driscoll. *What's real about virtual reality?: anthropology of, and in, cyberspace*. Visual Anthropology Review 8.2 (1992): 39-49
- [35] Escobar, Arturo. *Anthropology and the future: New technologies and the reinvention of culture*. Futures 27.4 (1995): 409-421

-
- [36] Rifkin, Jeremy, and Robert L. Heilbroner. *The end of work*. Jeremy P. Tarcher, 1994
- [37] János Varga, Ágnes Csiszárík-Kocsir, *The Impact of Human Activity on Environmental Elements Based on the Results of a Primary Research*. Acta Polytechnica Hungarica 21(12):147 (2024)
doi:10.12700/APH.21.12.2024.12.9
- [38] Brynjolfsson, Erik, and Andrew McAfee. *The second machine age: Work, progress, and prosperity in a time of brilliant technologies*. WW Norton & company, 2014
- [39] Özpençe, Aylin İdikut (2024) *Brain rot: overconsumption of online content (an essay on the publicness social media)*. Journal of Business Innovation and Governance, 7.2: 48-60
- [40] Enikő Nagy, Social and Sexual Robots (2025) *Technological Development, Social Acceptance and Ethical Challenges*. Acta Polytechnica Hungarica, 22(1):265 doi:10.12700/APH.22.1.2025.1.14
- [41] Cacioppo, John T., James H. Fowler, and Nicholas A. Christakis (2009) *Alone in the crowd: the structure and spread of loneliness in a large social network*. Journal of personality and social psychology 97.6:977
- [42] Baumer, Sonja (2023). *Social media, human connectivity and psychological well-being*. The SAGE handbook of digital technology research. (2013): 71-86. doi:10.4135/9781446282229.n6
- [43] Fuchs, D., Di Giulio, A., Glaab, K., Lorek, S., Maniates, M., Princen, T., & Røpke, I. (2016) *Power: the missing element in sustainable consumption and absolute reductions research and action*. Journal of cleaner production, 132, 298-307. doi:10.1016/j.jclepro.2015.02.006
- [44] Tibor Sipos (2023) *Cognitive Dissonance on Sustainable Mobility*. Acta Polytechnica Hungarica 20(5):31. doi:10.12700/APH.20.5.2023.5.3
- [45] Inés López-Baldominos, Vera Pospelova, Ana Castillo-Martínez, Luis Fernández-Sanz, Aleksandra Revina, Nina Rizun (2025) *How IT Professionals Perceive Artificial Intelligence Myths*. Acta Polytechnica Hungarica 22(1):163. doi:10.12700/APH.22.1.2025.1.9
- [46] Hertwich, E. G. (2005) *Consumption and the rebound effect: An industrial ecology perspective*. Journal of Industrial Ecology, 9(1-2), 85-98. doi:10.1162/1088198054084635
- [47] Allcott, H., & Greenstone, M. (2012) *Is there an energy efficiency gap?* Journal of Economic Perspectives, 26(1), 3-28. doi:10.1257/jep.26.1.3
- [48] Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C.,
-

- Hertwich, E., Khosla, R., Mattauch, L., Minx, J., Ramakrishnan, A., Rao, N. D., Steinberger, J., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018) *Towards demand-side solutions for mitigating climate change*. *Nature Climate Change*, 8, 260–263. doi:10.1038/s41558-018-0121-1
- [49] Trincado Aznar, Estrella, and José María Vindel (2023) *Energy Efficiency, Productivity and the Jevons Paradox*. *Science, Technology and Innovation in the History of Economic Thought*. Cham: Springer Nature Switzerland, 2023. 109-137
- [50] Alcott, B., Giampietro, M., Mayumi, K., & Polimeni, J. (2012) *The Jevons paradox and the myth of resource efficiency improvements*. Routledge. doi:10.4324/9781849773102
- [51] Harry D. Saunders (2008) *Fuel conserving (and using) production functions*. *Energy Economics*, 30(5), 2184-2235. doi:10.1016/j.eneco.2007.11.006
- [52] Gillingham, K., Kotchen, M. J., Rapson, D. S., & Wagner, G. (2016) *The rebound effect is overplayed*. *Nature*, 493, 475–476. doi:10.1038/493475a
- [53] Briscoe, M. D. *The paperless office twenty years later: Still a myth?* *Sustainability: Science, Practice and Policy*, 18(1), (2022) 837-845. doi:10.1080/15487733.2022.2146370
- [54] Sorrell, S., & Stapleton, L. (2018) *Rebound effects in UK road transport*. *Energy Policy*, 113, 715–730. doi:10.1016/j.enpol.2017.11.062
- [55] Turner, Richard. *The myth of the paperless office*. *New Library World*, 2003, 104.3: 120-121. doi:10.1108/03074800310467043
- [56] Freire-González, Jaume. *Governing Jevons' Paradox: policies and systemic alternatives to avoid the rebound effect*. *Energy Research & Social Science* 72 (2021): 101893. doi:10.1016/j.erss.2020.101893
- [57] Morgan, Jamie (2020) *Degrowth: necessary, urgent and good for you*. *Real-World Economics Review* 93: 113-131
- [58] Büchs, M., & Koch, M. (2019) *Challenges for the degrowth transition: The debate about wellbeing*. *Futures*, 105, 155-165. doi:10.1016/j.futures.2018.09.002
- [59] Leoni, D., Jackson, A., & Jackson, T. *Capping Resources to Achieve Sustainability: A Post-Growth Scenario Analysis*. *Social Science Research Network*, SSRN:5131164. <https://dx.doi.org/10.2139/ssrn.5131164>
- [60] Lawn, P. (2011) *Is steady-state capitalism viable? A review of the issues and an answer in the affirmative*. *Annals of the New York Academy of Sciences*, 1219(1), 1-25. <https://doi.org/10.1111/j.1749-6632.2011.05966.x>