Transformations and Sustainability, *1*(4) (2025) 300–327
https://doi.org/10.63775/hk5d1t79

From Jevons to Khazzoom-Brookes: Why energy efficiency alone won't lead to sustainability

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Abstract

Energy efficiency is extensively advocated as a fundamental sustainability strategy; nevertheless, historical and empirical evidence indicates that improvements in energy efficiency frequently result in heightened energy use instead of absolute reductions. The Jevons Paradox, further elaborated as the Khazzoom–Brookes Postulate, manifests when improvements in energy efficiency reduce the cost of energy services, thereby stimulating increased energy consumption at the individual, industrial, and macroeconomic levels. Rebound effects occur in transportation, manufacturing, and digital technologies, where improvements in energy efficiency often lead to increased overall energy consumption. This analysis investigates the extent to which these dynamics apply to the renewable energy transition, wherein efficiency improvements in solar, wind, and battery storage frequently result in heightened power demand instead of equivalent fossil fuel displacement.

Keywords: Jevons Paradox, Khazzoom-Brookes Postulate, energy efficiency, rebound effect, renewable energy, sustainability policy, energy sufficiency.

1. Introduction

Energy efficiency has always been considered a crucial component of sustainable development and climate mitigation efforts. Governments, international organizations, and business leaders have promoted energy efficiency improvements as a cost-effective strategy to reduce energy use, alleviate environmental harm, and increase economic output. The justification for energy efficiency initiatives is evident: employing less energy to achieve equivalent output should lead to a decrease in total energy demand and, consequently, reduced greenhouse gas (GHG) emissions.

In global climate policy, energy efficiency is often depicted as a synergistic solution—reducing expenses for businesses and consumers while simultaneously addressing energy security and environmental challenges. Energy efficiency gains could account for nearly 40% of the emissions reductions required to achieve the Paris Agreement's targets, as the International Energy Agency (IEA) has frequently emphasized energy efficiency as the "first fuel" for reducing global emissions (*Energy Efficiency - Energy System*, n.d.; *How Energy Efficiency Will Power Net Zero Climate Goals – Analysis*, 2021). The European Union's Energy Efficiency First approach

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Received 23 July 2025; **Accepted** 22 December 2025; **Published** 24 December 2025

emphasizes energy efficiency as the primary means for achieving a fair and economically sustainable energy transition (*Energy Efficiency First Principle*, n.d.).

Still, despite several decades of energy efficiency enhancements throughout all sectors (from industrial manufacturing and transportation to household appliances and digital infrastructure) total global energy consumption continues to rise. Despite advancements in the energy efficiency of technologies, the energy demand keeps growing, driven by economic expansion, population growth, and enhanced accessibility to energy-intensive goods and services. This counterintuitive outcome raises critical questions about the ongoing efficacy of policies and strategies aimed at improving energy efficiency as instruments for achieving sustainability (Özsoy, 2024; Wu & Lin, 2022).

The Jevons Paradox (Alcott, 2005) is the term used to describe the scenario in which the energy consumption of an object increases as a result of its increased energy efficiency, rather than a decrease. British economist William Stanley Jevons first articulated this concept in his 1865 publication "The Coal Question" (B. Clark & Foster, 2001). It was predicated on the quantity of coal consumed in Britain during the 1800s. Jevons stated that although steam engines improved in converting coal into useful energy, they also became more economical, resulting in an increase in coal consumption rather than a reduction. This peculiar phenomenon, in which increased energy efficiency results in heightened demand rather than reduced overall consumption, contradicts the notion that technical progress invariably promotes resource conservation (Alcott, 2005).

The Jevons Paradox extends its implications beyond the coal industry and remains highly relevant in contemporary energy issues. When technologies learn to consume less energy, they frequently become cheaper, simpler to find, and more widely employed, which leads to an overall rise in energy use (Giampietro & Mayumi, 2018). Numerous current examples of this dilemma exist:

- Transportation. Fuel-efficient vehicles reduce fuel expenses per kilometer; nevertheless, more driving offsets any financial and economic benefits or advantages.
- Manufacturing. Resource-efficient production methods reduce costs, resulting in reduced costs and increased availability of goods, hence promoting greater consumption.
- Digitalization. The rapid growth of digital services is facilitated by energy-efficient data centers and computing technology. This has resulted in a significant increase in demand for cloud computing and AI technologies, which consume substantial amounts of electricity.

In the 1980s, economists Daniel Khazzoom and Leonard Brookes expanded upon Jevons' concepts to offer recommendations for contemporary energy policy. The Khazzoom-Brookes Postulate (Saunders, 1992) posits that in an economy where energy significantly contributes to growth, improvements in energy efficiency result in increased economic activity, thereby elevating total energy consumption. Policies and measures aimed at improving energy efficiency can reduce energy consumption for an individual process or piece of equipment. But they may adversely affect the entire system, resulting in an increase in overall energy usage. This significantly impacts the notion that energy efficiency alone may achieve sustainability (Giampietro & Mayumi, 2018).

There is wide-spread opinion that energy efficiency was a crucial component of initiatives that promote sustainability. Policymakers, international organizations have identified enhancements in energy efficiency as a key method to reduce greenhouse gas emissions and strengthen energy security. But despite improvements in energy efficiency throughout the decades, global energy demand continues to rise rapidly. And this highlights a significant inquiry: could energy efficiency alone achieve sustainability, or does it potentially sustain escalating consumption patterns?

This paper critically examines the assumption that energy policies related to efficiency lead to a sustainable reduction in energy consumption. Of course, energy efficiency improvements undoubtedly benefit both the economy and the environment at the level of individual devices or sectors; nevertheless, they also initiate feedback loops within the sectors, referred to as rebound effects and can diminish or even negate the planned energy savings (Azevedo, 2014). Jevons paradox is in opposition to the popular paradigm of energy policy, which prioritizes energy efficiency over demand reduction. According to this, the review has three main objectives:

1. To analyze the historical and theoretical foundations of the Jevons Paradox and Khazzoom-Brookes Postulate, demonstrating their relevance to contemporary energy transitions. These concepts explain why efficiency-driven cost reductions often result in increased energy consumption rather than a decrease (Saunders, 1992).

2. To analyze practical examples of rebound effects in several sectors as transportation, manufacturing, and digitalization, where enhancements in energy efficiency frequently result in increased energy consumption (Beppler & Oliver, 2021; Du et al., 2020; Dütschke et al., 2021). This study will examine the renewable energy sector, where enhanced efficiency in renewable energy sources and related technologies (solar, wind, and battery storage) have resulted in increased power demand rather than a proportional reduction in fossil fuel consumption.

3. To explore alternatives that extend beyond basic energy efficiency, for example energy sufficiency, demand-side management, and post-growth economic frameworks. This analysis will examine how integrating energy efficiency with substantial systemic changes may yield genuine sustainability outcomes, in light of the issues associated with the rebound effect.

This study aims to contribute to the continuing discourse on global energy and climate policy. According to the International Energy Agency's Net Zero by 2050 roadmap (*Net Zero by 2050 – Analysis*, 2021) and the International Energy Agency's report (*Energy Efficiency - Energy System*, n.d.; *How Energy Efficiency Will Power Net Zero Climate Goals – Analysis*, 2021), energy efficiency enhancement is a critical component of carbon emission reduction and should comprise more than 40% of all emissions reductions. However, these predictions do not fully consider the potential for demand to increase due to energy efficiency. The European Union's Energy Efficiency First strategy prioritizes energy efficiency in policy formulation; yet, it lacks sufficient mechanisms to mitigate rebound effects or ensure a specified reduction in energy use (Mandel, Kranzl, et al., 2022; Mandel, Pató, et al., 2022). Without the incorporation of energy efficiency within a broader demand-side framework, such programs may provide only marginal energy efficiency improvements rather than a reduction in total energy consumption.

This evaluation boosts doubts about the idea that only developments in technology can lead to sustainability. Notwithstanding rapid advancements in energy efficiency, worldwide energy use continues to increase. This places policymakers in an awkward position: Is it possible to attain sustainability without fundamentally altering our energy consumption and economic processes? The analysis indicates that in the absence of explicit limitations on energy use, enhancements in energy efficiency are likely to maintain economic expansion and escalate energy usage, which is adverse to long-term sustainability.

2. Historical perspectives on energy efficiency and consumption

The importance of energy efficiency in sustainability necessitates an examination of its historical evolution. Technological advancements have consistently improved energy efficiency from the Industrial Revolution to modern energy transitions. Historical trends indicate that improvements in energy efficiency often result in heightened overall energy consumption instead of reductions, a phenomenon aptly exemplified by the Jevons Paradox and its contemporary extensions.

The Jevons Paradox originates from William Stanley Jevons' work, "The Coal Question" (1865) (B. Clark & Foster, 2001). Jevons, an English economist, observed that enhancements in steam engine efficiency, particularly those implemented by James Watt, led to an increase in coal consumption in 19th-century Britain, rather than a reduction (Jevons, 1866). Jevons argued that the enhanced efficiency of steam engines diminished the costs linked to coal-powered industrial activities, making coal a more attractive and economical energy source. Consequently, industries expanded, production escalated, and coal consumption soared (B. Clark & Foster, 2001).

Jevons' finding challenges the dominant belief that increased energy efficiency leads to energy conservation. Jevon revealed that enhanced efficiency fosters economic expansion and resulting in increased resource extraction and consumption. This finding remains relevant in contemporary discussions around sustainability and energy efficiency. Numerous historical instances illustrate the persistent relevance of the Jevons Paradox across diverse energy systems:

1. Coal and the Industrial Revolution (19th Century). At this century steam engines became more energy-efficient, which made coal-powered production less energy demanding and cheaper per production unit (Howes, 2023). But instead of decreasing coal usage, industrial activity grew, resulting in an unprecedented surge in coal demand (G. Clark & Jacks, 2007).

2. Oil and the Automotive Industry (20th Century). The advancement of fuel-efficient internal combustion engines initially decreased fuel consumption per car (Tao et al., 2009). Nonetheless, reduced operating expenses promoted elevated car

ownership rates and extended driving distances, hence augmenting total oil consumption.

3. Electricity and Digital Technologies (21st Century). Development and revolution in energy-efficient computing, such as enhanced microprocessors and cloud-based storage, have markedly decreased energy consumption per computation (Muralidhar et al., 2022). However, energy consumption in data centers, cryptocurrency mining, and artificial intelligence has surged, surpassing improvements in energy efficiency (2024 Report on U.S. Data Center Energy Use, 2024).

These historical instances illustrate that improvements in energy efficiency, while beneficial in many technical and economic respects, have repeatedly stimulated economic expansion and increased resource consumption rather than producing absolute reductions in energy use. Although Jevons' observations were rooted in 19th-century coal consumption, contemporary economists Daniel Khazzoom and Leonard Brookes have expanded his ideas to current energy systems. Released in the 1980s, their research resulted in the formulation of the Khazzoom-Brookes Postulate (Saunders, 1992), which contends that in an economy where energy is a primary catalyst for growth, enhancements in energy efficiency do not inherently result in reduced total consumption. By decreasing the cost of energy services, energy efficiency fosters heightened economic activity, which ultimately elevates overall energy demand.

The postulate (Saunders, 1992) could be divided into two main perspectives:

1. Microeconomic Perspective (Khazzoom's Contribution). As energy efficiency enhances, the effective expenditure on energy services diminishes (e.g., fuel costs per kilometer in transportation, unit costs in production). Consumers and businesses react and amplify their energy-intensive economic activities, what result in a direct rebound impact at the usage or utility level (Gillingham et al., 2016).

2. Macroeconomic Perspective (Brookes' Contribution). Efficiency-oriented cost reductions at the national or global level foster economic growth and industrial expansion. This expansion increases total energy demand, negating efficiency gains at the aggregate level. In energy-dependent economies, enhancements in energy efficiency may lead to backfire, resulting in an increase in total energy consumption instead of a decrease (Saunders, 2000).

The Khazzoom-Brookes Postulate, initially a theoretical concept, has received empirical validation from numerous investigations across diverse sectors. Several notable examples include:

1. Expansion of the Industrial Sector in China and India. Research in Energy Policy revealed that, despite significant advancements in energy efficiency within China's manufacturing sector, overall energy consumption persisted in increasing due to swift industrial expansion (chinapower2017, 2016; Shen & Lin, 2017). In India, industrial energy demand has risen concurrently with energy efficiency improvements, since reduced prices have facilitated increased production (Sahu, 2008; Soni et al., 2017).

2. Fuel Efficiency in Transportation. Studies on enhancements in vehicle fuel efficiency in the United States and Europe indicate that, despite legislative requirements for more fuel-efficient automobiles, overall fuel consumption continues to be elevated (Klier & Linn, 2011; Lutsey & Sperling, 2005). This phenomenon is attributed to the "rebound effect"—as the costs of driving decrease, vehicle ownership rates rise, and individuals travel greater distances. The U.S. Energy Information Administration (EIA) estimates that fuel efficiency rules may have diminished individual vehicle emissions; but, total emissions from transportation have persisted in increasing (*Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)*, n.d.; *Use of Energy Explained*, n.d.).

3. Digitalization and Energy Demand. The swift energy efficiency improvements in digital technologies, such as data centers and cloud computing, have not diminished overall electricity use (Chen, 2025). As computing power has grown more affordable and accessible, the global demand for digital services has surged. As the IEA observed, electricity demand in data centers has been consistently growing, where Artificial Intelligence (AI) applications and cryptocurrency mining intensify energy demand globally (Hebous & Vernon-Lin, 2024).

Notwithstanding increasing empirical evidence, current energy strategies frequently neglect to consider the comprehensive ramifications of the Khazzoom-Brookes Postulate. Numerous energy efficiency-oriented techniques persist in presuming that technological progress will result in a net decrease in energy use. Nonetheless, in the absence of supplementary steps to curtail overall consumption, energy efficiency improvements may exacerbate economic growth instead of fostering sustainability.

The European Union's Energy Efficiency Directive underscores the enhancement of energy performance in businesses, transportation, and buildings. Of course, these interventions are crucial, but they do not specifically tackle system-wide rebound effects or suggest restrictions on overall energy consumption. And this is very important when talking about final result. Global net-zero strategies often presume that energy efficiency will significantly contribute to emission reductions, neglecting its capacity to incite additional economic activity and demand. And these assumptions as ceteris paribus could be wrong (*Energy Efficiency Directive*, n.d.; von Malmborg, 2024).

The Khazzoom-Brookes Postulate also prompts broader inquiries regarding the relationship between energy efficiency and economic models. Improvements in energy efficiency that contribute to economic prosperity may inadvertently reinforce consumption-driven growth patterns that are fundamentally energy-intensive. The main idea of "green growth" says that economic expansion can happen without using more resources, but only by making things more energy-efficient (Hickel & Kallis, 2020). And this goes against each other. To really achieve sustainability, we may need to rethink our economic structures so that they put well-being and ecological stability ahead of constant growth (Jackson, 2009).

The Khazzoom-Brookes Postulate is still relevant in the present shift in energy. Improvements in energy efficiency can boost performance and save money, but they often lead to habits that use more energy overall. Policymakers need to realize that energy efficiency alone won't cut energy use enough, thus they need to combine efficiency measures with demand-side policies to avoid rebound effects. Without these steps, the global push for energy efficiency could ironically make environmental and resource problems worse instead of better (Özsoy, 2024).

Many studies and real-world patterns show that these contradictory consequences are still happening in today's energy transitions:

1. Energy Efficiency Recovery in Transportation. Fuel-efficient cars have cut down on the amount of fuel they use each kilometer by a lot. Still, increasing fuel efficiency has led to more people owning cars, longer commutes, and higher overall fuel demand. According to research, rebound effects in transportation could cancel out 30–60% of the expected fuel savings (A. Greening et al., 2000; Gottron, 2001; K. A. Small & Van Dender, 2005).

2. Enhancements in Manufacturing and Industrial Efficiency. The use of high-efficiency industrial gear has cut down on the cost of energy in manufacturing. As a result, industries have made more goods, which has led to higher overall energy use. This is especially true in economies that are growing quickly, like China and India (Kumar. J & Majid, 2020; Tang, 2022).

3. Digitalization and the Expansion of Energy Demand. The IT industry has made a lot of progress in making things use less energy, like cloud computing and CPUs that use less electricity. Still, lower costs have led to a lot of growth in data use, AI processing, and blockchain infrastructures, which has quickly increased the amount of electricity that data centers use. The International Energy Agency (IEA) says that even though energy efficiency has gotten better, the need for energy in digital infrastructure keeps going up (*Data Centres & Networks*, n.d.; Spencer, 2024).

The Jevons Paradox and the Khazzoom-Brookes Postulate show that improvements to renewable energy don't always lead to sustainability. When renewable energy gets cheaper and more widely available, people tend to use more energy overall, which cancels out some of the benefits of decarbonization (Saunders, 1992). Despite this, governments often promote policy measures aimed at improving energy efficiency while giving less attention to absolute levels of total energy use. Such an approach insufficiently accounts for rebound effects and may lock societies into trajectories of rising consumption. (Özsoy, 2024). If making things more energy-efficient can't lower total consumption, then sustainability efforts need to include demand-side activities. Energy sufficiency laws, carbon pricing, and post-growth economic models are some possible solutions. More will be said about them in later sections.

In the past, improvements in energy efficiency have rarely led to a complete drop in energy use. Improvements in energy efficiency have always led to more economic activity, which in turn has led to more energy use, from the Industrial Revolution to the present day. The Jevons Paradox and the Khazzoom-Brookes Postulate show that energy efficiency alone is not enough to make a strategy for sustainability. Their effects on the transition to renewable energy show how important it is to rethink energy policies beyond just making technology more energy-efficient. The next section will look at how the rebound effect shows itself in today's renewable energy and digital economies. This will make the case stronger that demand-side solutions need to be added to energy efficiency.

3. The rebound effect and its impact on energy efficiency gains

Energy efficiency is widely seen as a basic way to use less energy and have less of an impact on the environment as pollution and other negative consequences go down. But behavioral and systemic reactions often make the predicted savings from energy efficiency improvements less likely. This is known as the rebound effect. This section looks at the different ways the rebound effect shows itself, its features, and real-world evidence of its impact in a number of areas. As was said previously, the rebound effect is when improvements in energy efficiency lead to more energy use, both directly and indirectly. This happens because energy efficiency lowers the effective cost of energy services, which makes them more attractive to businesses and consumers. Some energy efficiency gains are kept, but some are canceled out by more energy use (Sorrell, 2007). There are two basic types of rebound effects:

• Direct rebound. Users may consume more of a service as a product or process becomes more resource-efficient (Gillingham, 2018). For example, cars that use less petrol per kilometer lower the cost of gas per kilometer, which encourages more driving (K. Small & Van Dender, 2007).

• Indirect rebound effect. The money saved from making things more resource-efficient is used to pay for other goods or services that need energy to make. If a household saves money on power by using LED lights, they might use that money to buy more electronics, which would use more energy overall (Azevedo, 2014; Wei & Wang, 2020).

• Economy-wide rebound. Improvements in efficiency lower production costs on a macroeconomic level. This leads to more industrial output and economic activity, which in turn leads to higher overall energy use (*Energy Efficiency Improvements*, 2024; Özsoy, 2024).

The size of the rebound effect depends on the sector, energy prices, and how consumers act. In some cases, the rebound effect may be minimal, making up for only a small part of the energy efficiency gains. But in the worst cases, it could backfire, leading total energy use to be higher than the initial savings.

Studies across multiple industries have demonstrated the persistent occurrence of the rebound effect, despite vigorous energy conservation efforts. Examples illustrate that improvements in energy efficiency do not guarantee a decrease in overall energy consumption. Conversely, they often promote increased consumption, so negating some or all anticipated energy savings. These rebound effects manifest across a wide range of economic sectors:

1. Transportation. Improvements in vehicle fuel efficiency have led to decreased travel costs per kilometer. Research reveals that when cars attain higher fuel economy, the total distance traveled by vehicles increases (Akar & Guldmann, 2012; Ju et al., 2023; Y. Liu, 2009). This happens in countries with lower fuel prices, when

the incentive to drive increases. Research by the International Transport Forum indicated that the rebound effect in transportation ranges from 10 to 60 percent, depending on gasoline prices and income levels (Dimitropoulos et al., 2018).

2. Household Energy Use. The use of energy-efficient appliances, lighting, and heating systems has reduced energy consumption per unit. Nonetheless, households often respond by procuring supplementary equipment or maintaining higher comfort levels (e.g., raising home heating temperatures due to the improved energy efficiency of the heating system). Research in the United States indicated that residential energy efficiency programs resulted in a rebound effect of 20-40 percent, hence reducing the expected savings from these initiatives (A. Greening et al., 2000; Aydin et al., 2017; Thomas et al., 2014).

3. Industrial Sector. Improvements in manufacturing energy efficiency have lowered production costs, leading to heightened industrial activity. This happens in emerging economies marked by rapid industrialization. For example, China has implemented rigorous industrial energy efficiency regulations; yet, total industrial energy consumption continues to rise due to increased output volumes (Y. Yang & Lo, 2024; Zhou et al., 2010).

4. Digital Technologies and Data Centers. Advancements in energy savings in computers and data storage have made digital services more accessible and cost-effective. The proliferation of digital consumption, including cloud computing, artificial intelligence, and cryptocurrency mining, has significantly increased electricity demand (Kaur & Chana, 2015). The International Energy Agency forecasts a rise in global electricity usage by data centers, despite improvements in server and cooling energy efficiency (*Data Centres & Networks*, n.d.; Spencer, 2024).

The transition to renewable energy is deemed an essential approach for reducing carbon emissions and achieving sustainability. The worldwide implementation of solar, wind, and battery storage technologies has surged owing to improvements in energy efficiency that make them more economically viable. However, rather of producing conclusive reductions in total energy consumption, cost savings achieved through energy efficiency can result in an overall increase in energy demand. The renewable energy rebound effect presents concerns regarding the effectiveness of clean energy transitions in reducing fossil fuel consumption or potentially intensifying electricity demand (Galvin et al., 2021; Q. Wang et al., 2018).

A notable example of the rebound effect in the renewable energy sector is the increased electricity use by families and businesses following the installation of solar photovoltaic (PV) systems. Studies indicate that residences with rooftop solar panels typically utilize more electricity than those without, as they perceive solar energy as "free" or low-cost (Deng & Newton, 2017; Nguyen et al., 2024). This behavioral shift leads to heightened use of energy-intensive appliances, such as air conditioning, electric heating, and smart home technologies, so partially undermining the expected energy savings. In Germany, researchers found that residences equipped with residential solar panels augmented their electricity use by approximately 20% relative to those lacking solar panels (Atasoy et al., 2021; Frondel et al., 2022; Galvin, 2022). A similar trend has been observed in California, where the cost-effectiveness of solar energy has prompted a rise in energy demand rather than maintaining pre-installation consumption levels (Grant & Hicks, 2020; Kim & Trevena, 2021).

Wind energy as a crucial element of the renewable energy source, has also resulted in unexpected rises in total energy use. In regions where wind energy is economically advantageous relative to fossil fuels, related industries have expanded their operations due to the availability of cheaper electricity. China has rapidly augmented its wind energy capacity; but, rather from supplanting coal-fired electricity, a considerable fraction of this renewable energy has been employed to bolster the expansion of energy-intensive industries, such as steel and aluminum manufacturing. Instead of dismantling coal plants, China has relied on wind energy to meet rising electricity demand, leading to an overall increase in consumption (Davidson et al., 2016; Li et al., 2022; Y. Wang et al., 2023). A similar trend could be seen in Europe. In this region offshore wind energy has facilitated the expansion of sectors such as hydrogen production and electrified industrial processes (Durakovic et al., 2023; Glaum et al., 2024; Rogeau et al., 2023). While these breakthroughs promote decarbonization in specific areas, together they demonstrate that enhancements in renewable energy efficiency do not inherently lead to a decrease in total energy use.

A key issue affecting the renewable energy rebound effect is the growing electrification of transportation, particularly the increasing adoption of electric vehicles (EVs). Despite the fact that electric vehicles are more energy-efficient than internal combustion engine vehicles, their lower operating costs per kilometer encourage increased usage. In Norway, where electric car adoption is among the highest globally, research indicates that electric vehicle owners generally drive more than their gasoline or diesel counterparts, leading to increased electricity demand (Verleger, 2024; A. Yang et al., 2023). Moreover, as electric vehicle technology has progressed and become more economically viable, many consumers who formerly relied on public transportation have shifted to private vehicle ownership, hence augmenting energy consumption. This trend encompasses not just passenger vehicles but also freight and delivery firms that have expanded their electric fleets, hence increasing the overall energy consumption in the transportation sector. In regions where electricity generation remains reliant on fossil fuels, such as some sections of the United States and India, the increasing demand from electric vehicles may lead to elevated emissions if the expansion of renewable energy supply does not accelerate sufficiently to meet this need (Archsmith et al., 2022; Bakhtyar et al., 2023; Bruchon et al., 2024).

The growth of smart grids and digital energy management systems has also shown that making things more energy-efficient can lead to more energy use overall. Smart home technologies that are meant to make homes more energy efficient have, ironically, led to more demand since people keep their homes at more comfortable temperatures and use more electronic devices. Data centers that use less energy have made cloud computing, AI apps, and cryptocurrency mining expand quickly. Even though server energy efficiency and cooling technologies have gotten better and lowered the amount of energy used per unit, the total amount of electricity needed by digital services keeps going up (Balushi et al., 2022; Thangam et al., 2024). The International Energy Agency says that data centers will use a lot more electricity around the world in the next few years. This is because AI-driven computing and digital services are growing so quickly (Chen, 2025; *Executive Summary – Electricity 2024 – Analysis*, n.d.; Lane & Mayer, 2018; Linares et al., 2017). This is an example of a larger trend in which cutting costs to make services more energy-efficient makes them easier to get, which leads to more use instead of less total demand.

These numbers show that making renewable energy more energy-efficient doesn't always mean that people will use less energy overall. On the other hand, they often lead to more economic activity, which means that many industries use more energy. The falling costs of solar and wind energy have made it easier for people in developing countries to get electricity, which has enhanced their quality of life while also keeping up with the historical trend of rising energy demand (Cai et al., 2024; Dirma et al., 2024; Osman et al., 2023). This is a big step forward for social and economic growth, but it also shows how hard it is to cut energy use completely just by becoming more energy-efficient. In industrialized countries, the availability of cheap renewable electricity has led to the proliferation of energy-intensive uses like electric heating, smart infrastructure, and large battery storage, which has caused electricity demand to go up in general (Osman et al., 2023).

These changes make it hard to believe that making renewable energy better will immediately make it more sustainable. If there aren't clear limits on overall energy consumption, making renewable energy more energy-efficient could accidentally keep the problem they want to remedy going. Policymakers need to understand that just being energy-efficient isn't enough. They need to take other steps, including making sure there is enough energy, setting prices for power that go up over time, and putting rules in place on the demand side, to keep renewable energy from making consumption levels worse. Clean energy technologies are vital for lowering carbon emissions, but they need to be part of a wider plan that focuses on using less energy instead of just making things work better and cheaper. If not, the move to renewable energy could continue the same way as earlier technical advancements that were made to save money, which would keep the Jevons Paradox going instead of addressing it.

Because the rebound effect lasts so long, it is exceedingly hard for energy policy and plans for sustainability to work. If energy efficiency alone can't cut total consumption, we need to find other ways to make sure that improvements in energy efficiency help the environment. Regarding to this, essential policy considerations could encompass:

• Beyond energy efficiency-first approaches. Energy efficiency is at the top of the list of options for many energy programs. However, efforts to be more sustainable need to involve big plans that look at how much energy is used overall (Della Valle & Bertoldi, 2022; Wiese et al., 2024).

• Energy sufficiency policies. Energy efficiency is about getting better results, whereas sufficiency is about using less energy when it's not needed. Policies that encourage people to adjust their behavior, including limiting how much they eat, can help lessen rebound effects (Fawcett & Darby, 2019; Segovia-Martin et al., 2023).

• Regulatory and economic mechanisms. Rules based on how much energy is used, carbon pricing, and energy tariffs can assist turn improvements in energy efficiency into substantial cutbacks in resource consumption (*Carbon Pricing Design*, 2020; Parry et al., 2022).

• Post-growth and degrowth strategies. If economic growth keeps pushing up energy demand, we may only be able to make large cuts if we change how we think about growth (Hardt et al., 2020; Kikstra et al., 2024).

The rebound effect is still a huge challenge that makes it challenging to genuinely make energy efficiency work for the long term. Even while new technologies use less energy per unit, the lower costs generally lead to higher use, which cancels out a lot of the promised savings. This is happening in transportation, industry, residences, and digital technology, and it is becoming more critical as we move toward renewable energy. To fix this issue, lawmakers need to do more than just establish plans that focus on energy efficiency. They also need to take actions to cut overall energy use. The global hunt for energy efficiency could make long-term environmental problems worse instead of better if there aren't any of these kinds of projects.

In the next section is about possible rules and other frameworks that could assist lessen the rebound effect and make sure that energy efficiency truly does help the environment in the long run.

4. Energy efficiency in the renewable energy transition

Many people think that solar, wind, and hydroelectric power are important parts of a sustainable energy system. They help us get rid of carbon by making us less dependent on fossil fuels (Farghali et al., 2023; Osman et al., 2023). But when advances in energy efficiency make renewable energy cheaper and more widely available, they may also lead to an increase in total energy use. This section looks at how the Jevons Paradox and the rebound effect show up in the shift to renewable energy. It talks about both the good and bad effects of making clean energy technology more energy-efficient.

Energy efficiency is very important for making renewable energy systems work better. Solar panels, wind turbines, and energy storage technologies that work better cost less and provide more energy for every unit of input. Some of the benefits of making renewable energy sources more energy-efficient are:

• Lower expenses of manufacturing. As energy efficiency increases, the levelized cost of electricity (LCOE) from renewables declines, making clean energy more accessible and competitive with fossil fuels (Bolinger et al., 2022; Renewable Power Generation Costs in 2022, 2023).

• Higher energy yield. More energy-efficient solar panels and wind turbines provide more electricity from the same number of resources, which makes land usage more energy-efficient (Haga et al., 2019; Ogundipe et al., 2024).

• Enhanced storage and grid integration. New battery technologies and smart grids help control demand better and cut down on energy losses (Kushawaha et al., 2024; Sharma, 2024).

While these technological advancements play a crucial role in decarbonizing energy systems, they also introduce new challenges, particularly when improvements in renewable energy efficiency stimulate additional energy demand rather than directly displacing fossil fuel use. Although renewable energy is central to climate mitigation strategies, making clean energy production more energy-efficient does not necessarily result in lower aggregate energy consumption. Instead, a number of rebound mechanisms can happen:

1. Lower Energy Costs Lead to Higher Consumption. Electricity use generally goes up as solar and wind power get cheaper since it is easier to afford. Households and businesses that used to care about saving energy may now consume more electricity overall, which might make up for part of the carbon savings. Lower costs for renewable energy in developing nations can quickly increase access to energy, which is good for development but also increases global energy demand (Osman et al., 2023; *Renewable Energy – Powering a Safer Future*, n.d.).

2. The Expansion of Energy-Intensive Industries. The expansion of energy-intensive businesses like crypto-currency mining, artificial intelligence processing, and large-scale manufacturing has been helped by the availability of cheap renewable electricity. For instance, data centers currently use more and more electricity, and even while computing and cooling technologies are becoming more energy-efficient, they still use more energy (2024 Report on U.S. Data Center Energy Use, 2024; Otto et al., 2023).

3. Electrification and the Growth of New Energy Uses. Even while electric vehicles (EVs), heat pumps, and industrial electrification are more energy-efficient than fossil fuel-based solutions, they all use more electricity overall. Sometimes, switching to renewable energy and electrification leads to more energy use overall instead of just replacing fossil fuels (Jadun et al., 2017; Lee, 2022).

These patterns show that while making renewable energy more energy-efficient is good, it doesn't automatically mean that total energy demand will go down. Instead, they typically encourage people to use more energy, which makes demand-side policies even more important. Real-world evidence suggests that making renewable energy technology more energy-efficient can lead to higher energy demand:

1. Solar Power and Residential Energy Use. People who have solar panels on their roofs often use more electricity because they think solar energy is "free" or cheap. Research in Germany found that residences with solar panels on their roofs used up to 20% more electricity than homes without them, which largely canceled out the benefits of being environmentally friendly (Atasoy et al., 2021; Frondel et al., 2022, 2022; Galvin, 2022; Willms & Matthies, 2016).

2. Wind Energy and Industrial Expansion. Many energy-intensive sectors have grown instead of cutting back on their energy use as wind power has become cheaper. The rapid growth of wind energy in China has been matched by a rise in demand for

industrial power, which has stopped fossil fuel use from falling by the same amount (Davidson et al., 2016; Li et al., 2022; Y. Wang et al., 2023).

3. Electric Vehicles and Total Transportation Energy Demand. Electric vehicles (EVs) are better for the environment than cars with internal combustion engines, but reduced running costs make people drive more, which uses more energy overall. A study of EV adoption in Norway found that even while individual vehicle emissions went down, the transport sector's overall electricity demand went up a lot, which meant that more energy had to be made (Verleger, 2024; A. Yang et al., 2023).

These case studies show that making renewable energy more energy-efficient can have unforeseen effects. Instead of lowering total energy use, they typically make it higher. As renewable energy technologies get better and cheaper, they are being used on a scale never seen before. This change is very important for reducing carbon emissions, but it's becoming clear that just making things more energy-efficient won't lead to lower energy demand. Instead, they often lead to more consumption, which keeps patterns of economic growth going that keep or even increase overall energy demand. Without clear steps to control demand, energy efficiency and the use of renewable energy could end up making people use more resources instead of helping the environment. This shows how important it is to have rules on the demand side that not only make energy use more energy-efficient but also limit wasteful consumption and make sure that energy efficiency increases really do lead to less harm to the environment.

Progressive energy pricing schemes that prevent people from using too much electricity (Özsoy, 2024) are one of the best strategies to fight the rebound effect. Many of the ways that electricity prices are set today encourage people to use more energy. For example, large industrial customers generally get lower rates when they buy a lot of electricity at once, which makes it cheaper to use more energy instead of saving it. A move toward tiered power pricing, where people who use more electricity pay more for it, could help make sure that energy efficiency gains don't just lead to more demand. In other places, like Japan and California, this method has worked well. Households and businesses who consume more over a particular amount of energy pay much higher prices (Fry, 2023; Hasegawa, 2021). But political pressure from energy-intensive companies and pushback from industrial sectors frequently make it harder for more people to use these kinds of measures.

Energy sufficiency policies are another important demand-side technique. They go beyond energy efficiency by putting clear restrictions on how much energy can be used. Policies that focus on sufficiency are different from those that focus on energy efficiency improvements, which aim to get the same or more output with less energy. Instead, energy sufficiency policies aim to cut down on energy use as much as possible. This could mean limiting the use of energy in non-essential areas, such banning bitcoin mining that uses a lot of energy, limiting the use of air conditioning in commercial buildings, or setting limits on the hours that high-energy industries can work. Some European countries have tried out energy sufficiency approaches, especially after the energy crisis that happened when geopolitical events disrupted fossil fuel supplies. For instance, France and Germany put in place temporary energy restriction measures to cut down on use in the winter months. This shows that such policies can work and be politically possible when presented as remedies to critical problems (Amelang & Wehrmann, 2023; Creedon, 2022).

National or sectoral energy caps are examples of regulatory actions that are a more organized way to manage demand. Governments might make sure that energy efficiency increases actually lead to less resource use instead of more by setting maximum energy consumption limitations for industries, regions, or even whole economies. Even though these kinds of actions aren't common in market-driven economies, there are few examples from history. Sweden adopted tight construction energy rules in the 1970s that not only encouraged energy efficiency but also set strict limitations on heating energy per square meter. This cut down on overall demand in the long term (Sprei et al., 2006). China's "dual control" policy on energy use and intensity has tried to limit energy use in heavy sectors more lately, although implementation is still not always consistent because of economic constraints ('China to Ease Energy Use Curbs to Relieve Economic Pressures', 2021; H. Liu et al., 2023).

Urban and infrastructure planning are very important for determining long-term energy demand, in addition to rules and regulations. Poorly built infrastructure keeps society locked into high levels of energy use by making things like long-distance travel, cooling high-rise offices, and suburban sprawl more common. Investing in compact city design, public transit systems, and shared energy systems can cut down on the demand for private vehicles and heating and cooling that use a lot of energy. Countries like Denmark and the Netherlands have shown that integrated urban planning that supports cycling infrastructure, district heating, and energy-efficient building design may lower per capita energy consumption over time without lowering quality of life (Buehler & Pucher, 2020; Dal Cin et al., 2021; Gürsan et al., 2023; Johansen, 2022). But these kinds of adjustments to the structure need long-term policy commitment and financial investment, which makes them hard to do in countries where short-term economic growth is more important.

Even if demand-side strategies have apparent benefits, there are still big problems that make it hard for them to be used by everyone. One of the biggest problems is that sectors and consumers who are used to having free access to energy are against it. When governments try to put in place energy sufficiency requirements, they often get pushback from firms that are worried about losing their competitive edge and from consumers who are worried about how these measures would affect their way of life (Braunerhjelm & Henrekson, 2024; Jones et al., 2024; Loch-Temzelides, 2024). Also, it's hard to justify policies that clearly want to restrain consumption while economic models show that GDP will keep growing. A lot of the time, policymakers would rather focus on technology solutions, such expanding renewable energy and capturing carbon, than deal with the structural problem of rising energy demand (Jakimowicz, 2022; Kabeyi & Olanrewaju, 2022).

The Paris Agreement and the Net Zero by 2050 roadmaps (Costa et al., 2022) are two examples of international climate frameworks that focus more on supply-side solutions than on cutting demand. They often talk about energy efficiency as a major goal, but they don't often push for specific policies that would limit total energy use.

This shows that policymakers around the world are not willing to admit that there are trade-offs between growing the economy and cutting energy use to zero. Without more institutional support for demand-side initiatives, there is still a chance that energy efficiency gains may keep driving economic growth instead of real sustainability (Segovia-Martin et al., 2023).

In the end, making sure that the switch to renewable energy leads to real cuts in energy use involves a change in both policy and economic thinking. Demand-side measures like progressive energy pricing, sufficiency rules, energy caps, and adjustments to infrastructure should be part of sustainability programs, not just something to think about later. The Jevons Paradox will continue if policymakers only focus on making things more energy-efficient and developing new technologies. The shift to renewable energy may also lead to higher energy use instead of real decarbonization. Not only do we need to make energy cleaner, but we also need to change how people think about energy use so that energy efficiency gains lead to real environmental advantages instead of just more growth and consumption.

Moving to renewable energy is important for fighting climate change, but making clean energy technology more energy-efficient doesn't always mean using less energy overall. Instead, they can encourage more consumption, which can lead to rebound effects that cancel out some of the benefits of sustainability. If policymakers don't take action on the demand side, the energy efficiency gains from renewables could lead to more overall energy demand instead of less fossil fuel use. Not only do we need cleaner energy for a truly sustainable energy transition, but we also need systemic plans to limit total consumption and make sure that energy efficiency leads to real sustainability outcomes.

5. Discussion

This review has looked at the Jevons Paradox and the Khazzoom-Brookes Postulate in a critical way in relation to sustainability and energy efficiency. Energy efficiency is often pushed as a key way to cut down on energy usage and lessen its effects on the environment. However, both historical and empirical evidence show that just making things more energy-efficient is not enough to guarantee that energy use will go down. Instead, energy efficiency gains often lead to more consumption, which has unforeseen effects that make sustainability efforts less effective.

Improvements in energy efficiency often have rebound effects. The Jevons Paradox and the Khazzoom-Brookes Postulate show that while using energy more efficiently makes it cheaper, people choose to consume more energy instead of less. Studies in a number of areas, including as transportation, industry, residential energy usage, and digital infrastructure, show that direct, indirect, and economy-wide rebound effects often reduce the energy savings that were predicted from energy efficiency measures.

There are rebound effects that can happen during the switch to renewable energy. Technological advances in solar, wind, and battery storage have made things cheaper and more energy-efficient, but they have also made people want more electricity. The fact that renewable energy is now cheaper has led to higher overall use, rather than a rigid one-to-one replacement of fossil fuels. The rapid growth of electric cars, digital services, and industrial electrification has made the need for a more comprehensive approach to sustainability even more urgent.

When talking about the drop in sustainable energy use caused by energy efficiency and the likely rebound effect, it's vital to separate the quantity of demand from the demand function and to include the supply function. This makes it easier to see and comprehend how a new equilibrium point for energy use might be reached. Based on the information in the paper, Fig. 1 demonstrates the several circumstances that could happen. The equilibrium point E, together with the demand function D and the supply function S, shows what the situation was like at first, before any improvements were made to technology (in terms of either energy efficiency or Renewable energy sources development). In the energy sector, there is a specific equilibrium between the price P_E and the quantity of energy used Q_E.

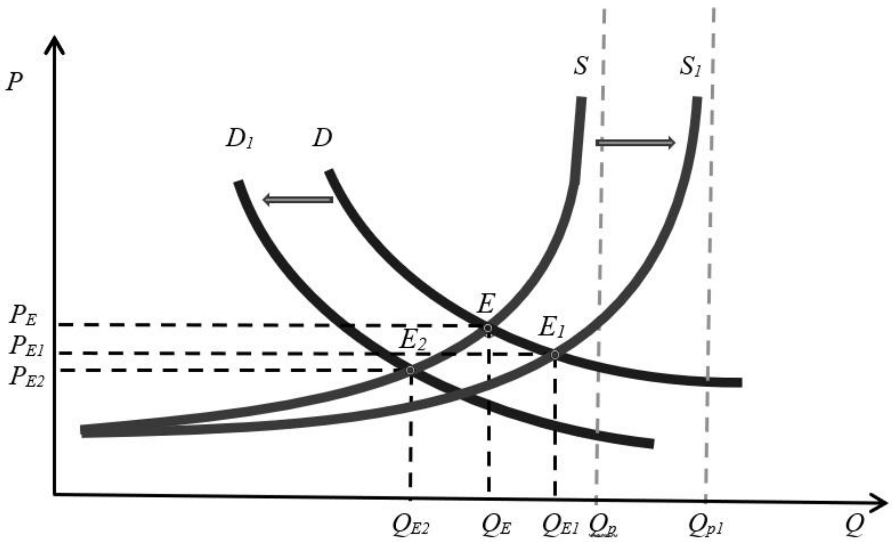

Fig. 1. Jevons Paradox: energy efficiency improvements and demand–supply shifts
Source: created by the authors

The new equilibrium point E_2 shows how the discussed gain in energy efficiency will affect energy use, assuming all other factors stay the same (*Ceteris paribus*). This is because the energy demand curve moves to the left. This is a case of less energy use ($Q_{E2}<Q_E$), which is what sustainable energy policy aims for and is predicted to happen as a result of better energy efficiency. But when you add in the fact that technological progress might increase the potential market capacity from Q_p to Q_{p1}, the theory of financial saturation says that the energy production supply function moves from S to S_1 (Girdzijauskas, 2024). In this situation, without considering the energy efficiency factor, another equilibrium point E_1 would be reached with higher energy quantity ($Q_{E1}>Q_E$). It is important to note that the shift of supply to the right is also a result of the Jevons paradox, which is shown in Slutsky's equation through the substitution and income effects. This is done to optimize consumer utility using the new consumer budget curve.

There are different possible points of equilibrium between the energy use of Q_{E2} and Q_{E1} when you look at both changes (shifts in demand and supply). The following things will determine whether the new equilibrium point's amount will be more or less than the former quantity Q_E:

• The effect of the shift of the curves: which shift in the supply or demand curve is bigger. The new equilibrium point will utilize less energy if the change in the demand curve induced by energy efficiency is bigger than the change in the supply curve. On the other hand, if the change in the supply function is bigger than the change in the demand function

• The price elasticity of both curves

• The fact that new equipment needs more energy because of technical progress doesn't mean that energy use is less energy-efficient.

So, when making energy policy and planning for sustainability by making things more energy-efficient, it's important to look at more than just the amount of demand. Other things to think about include the demand function, supply, the elasticity of these functions, users' utility maximization, and the development of new technology-driven equipment. So, further research and evaluation of the criteria described above is needed in order to make predictions that are more accurate and possible future outcomes.

Policies on the demand side must go along with energy efficiency. If there are no clear restrictions on how much energy may be used, gains in energy efficiency are likely to keep the economy growing instead of cutting energy consumption. We need to include energy efficiency in a bigger picture that includes demand-side measures like energy sufficiency rules, carbon pricing, energy caps, and post-growth economic models in order to solve this problem. These measures make sure that advances in energy efficiency lead to real sustainability outcomes instead of allowing more resource use.

6. Conclusions and future directions

The results show that we need to rethink the current emphasis on tactics that put energy efficiency first. Policymakers shouldn't see energy efficiency as a separate solution. Instead, they should include energy efficiency gains in a larger framework that focuses on managing demand and building sustainable economic structures. Technological advances in energy efficiency will not be able to provide long-term sustainability if the root causes of rising energy demand are not addressed.

To avoid the Jevons Paradox and make sure that energy efficiency really helps the environment, we need to change the way we think about energy and the economy. Policymakers need to go beyond just making things more energy-efficient and create structural changes that actively control how much energy people use. To make energy efficiency targets match sustainability goals, some critical directions should be given priority.

Suggestions for policies that can help manage demand. Energy policy needs to include solutions based on sufficiency that focus on lowering total energy use instead than just making things more energy-efficient. To decrease the chance of rebound effects, governments should put in place rules like energy limitations, progressive energy pricing, and carbon taxes. To promote low-energy lifestyles, urban infrastructure should be reconfigured with an emphasis on public transportation, compact city planning, and decentralized renewable energy systems. Also, sectors that don't serve society much, like cryptocurrency mining and high-energy artificial intelligence computations, should be limited in how much energy they can use.

Changes in the economy and the system. Sustainability efforts need to go beyond GDP growth as the main way to measure economic performance. Instead, they should focus on well-being, environmental stability, and fair resource distribution. To keep energy consumption within the limits of the planet, we should promote post-growth economic models that don't rely on constant growth. We also need to encourage circular economy strategies that put reuse, recycling, and saving energy ahead of endless material throughput. These modifications to the system would move the focus away from economic growth based on energy efficiency to a paradigm that actively controls total energy use.

Things that should be studied in the future. We need to do more research to find out just how much rebound effects affect new energy technologies like AI, smart grids, and electrified industrial systems. We need to do real-world research to see if sufficiency legislation and behavioral interventions really do lower overall energy demand. We also need to do more research to find out if absolute decoupling is possible. This means finding out if economies can keep good living standards while using less energy overall. Future research should focus on assessing policy changes in real life to make sure that energy efficiency techniques support long-term sustainability goals instead of being hurt by economic and behavioral feedback loops.

The Jevons Paradox and the Khazzoom-Brookes Postulate are two big problems for traditional stories about sustainability. Energy efficiency is still an important part of the clean energy transition, but it can't be the only way to cut down on energy use. Improvements in energy efficiency are likely to lead to more resource consumption instead of conservation if there are no ways to manage total demand. This fact highlights how important it is for both policy and economic frameworks to change quickly so that energy efficiency gains really lead to long-term sustainability.

To make the energy transition really sustainable, authorities need to rethink how energy is managed in economic systems. Using energy efficiency to keep the economy growing will only make the problem of rising energy use worse. Instead, a demand-focused approach that includes policies for sufficiency, regulatory actions, and reforming the economy is necessary to make real cuts in energy use. If these kinds of actions aren't taken, the historical trend of energy expansion driven by efficiency will continue, making it harder for the world to move toward a more sustainable future.

Energy efficiency can help make the world more sustainable, but only if it is part of a bigger change in how we use energy, how we do business, and how we act as a society. Society can only make an energy transition that is both technologically advanced and environmentally friendly by combining energy efficiency with a complete drop in energy consumption. This change will need brave policy decisions, cooperation amongst different fields, and a complete rethinking of how growth-oriented economic systems work. If these adjustments don't happen, advances in energy efficiency will keep falling short of the sustainability goals that the world needs right now.

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