Lawrence Berkeley National Laboratory
LBL Publications

Title

Energy Efficiency: What Has Research Delivered in the Last 40 Years?

Permalink

https://escholarship.org/uc/item/4nv295zh

Journal

Annual Review of Environment and Resources, 46(1)

ISSN

1543-5938

Authors

Saunders, Harry D
Roy, Joyashree
Azevedo, Inês ML
et al.

Publication Date

2021-10-18

DOI

10.1146/annurev-environ-012320-084937

Copyright Information

This work is made available under the terms of a Creative Commons Attribution-NonCommercial License, available at https://creativecommons.org/licenses/by-nc/4.0/

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

ANNUAL REVIEWS

Annual Review of Environment and Resources

Energy Efficiency: What Has Research Delivered in the Last 40 Years?

Harry D. Saunders,[1,*] Joyashree Roy,[2,3,*]
Inês M.L. Azevedo,[4,*] Debalina Chakravarty,[5]
Shyamasree Dasgupta,[6] Stephane de la Rue du Can,[7]
Angela Druckman,[8] Roger Fouquet,[9,*]
Michael Grubb,[10,*] Boqiang Lin,[11] Robert Lowe,[12,*]
Reinhard Madlener,[13,14,*] Daire M. McCoy,[9,15,*]
Luis Mundaca,[16,*] Tadj Oreszczyn,[17] Steven Sorrell,[18,*]
David Stern,[19,*] Kanako Tanaka,[20] and Taoyuan Wei[21]

[1]Carnegie Institution for Science, Global Ecology Group, Stanford, California 94305, USA; email: hsaunders@earthlink.net

[2]Sustainable Energy Transition Program, Department of Energy, Environment and Climate Change, Asian Institute of Technology, Klongluang, Pathumthani 12120, Thailand

[3]Department of Economics, Jadavpur University, Kolkata 700032, India

[4]Department of Energy Resources Engineering, Stanford University, Stanford, California 94305, USA

[5]Department of Economics, St. Xavier's University, Kolkata 700160, India

[6]School of Humanities and Social Sciences, Indian Institute of Technology Mandi, Himachal Pradesh 175005, India

[7]Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

[8]Centre for Environment and Sustainability, University of Surrey, Guildford, Surrey GU2 5XH, United Kingdom

[9]Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London WC2A 2AE, United Kingdom

[10]UCL Institute for Sustainable Resources, The Bartlett Faculty of the Built Environment, Bartlett School of Environment, Energy & Resources, University College London, London NW1 2HE, United Kingdom

[11]China Institute for Studies in Energy Policy, Xiamen University, Xiamen 361005, China

[12]UCL Energy Institute, University College London, London WC1E 6BT, United Kingdom

[13]School of Business and Economics/E.ON Energy Research Center, RWTH Aachen University, Aachen 52074, Germany

[14]Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

[15]The Economic and Social Research Institute, Dublin D02 K138, Ireland

[16]International Institute for Industrial Environmental Economics, Lund University, Lund SE-221 00, Sweden

ANNUAL REVIEWS CONNECT
www.annualreviews.org
- Download figures
- Navigate cited references
- Keyword search
- Explore related articles
- Share via email or social media

Annu. Rev. Environ. Resour. 2021. 46:135–65

First published as a Review in Advance on July 6, 2021

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-012320-084937

Copyright © 2021 by Annual Reviews. This work is licensed under a Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See credit lines of images or other third-party material in this article for license information

[*]These authors contributed equally to this review, and the remaining authors are listed alphabetically.

OPEN ACCESS CC BY

[17] Bartlett School of Environment, Energy & Resources, University College London, London WC1H 0NN, United Kingdom

[18] Science Policy Research Unit, University of Sussex, Brighton BN1 9RH, United Kingdom

[19] Crawford School of Public Policy, College of Asia & the Pacific, Australian National University, Canberra ACT 2600, Australia

[20] Center for Low Carbon Society Strategy, Japan Science and Technology Agency, Tokyo 102-8666, Japan

[21] Climate Economics Group, Center for International Climate Research (CICERO), 0318 Oslo, Norway

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Keywords

energy efficiency, energy intensity, efficiency policy, energy efficiency gap, public policy

Abstract

This article presents a critical assessment of 40 years of research that may be brought under the umbrella of energy efficiency, spanning different aggregations and domains—from individual producing and consuming agents to economy-wide effects to the role of innovation to the influence of policy. After 40 years of research, energy efficiency initiatives are generally perceived as highly effective. Innovation has contributed to lowering energy technology costs and increasing energy productivity. Energy efficiency programs in many cases have reduced energy use per unit of economic output and have been associated with net improvements in welfare, emission reductions, or both. Rebound effects at the macro level still warrant careful policy attention, as they may be nontrivial. Complexity of energy efficiency dynamics calls for further methodological and empirical advances, multidisciplinary approaches, and granular data at the service level for research in this field to be of greatest societal benefit.

Contents

1. INTRODUCTION 137
2. ENERGY EFFICIENCY DEFINED 137
3. HISTORICAL TRENDS 141
4. THE ENERGY EFFICIENCY GAP AND GROUNDS FOR POLICY INTERVENTION 143
5. POLICIES USED TO IMPROVE ENERGY EFFICIENCY 144
    5.1. Types of Policies 144
    5.2. Evidence of Direct Benefits 146
    5.3. Cost-Effectiveness of Energy Efficiency Programs 147
6. WIDER CONSEQUENCES OF ENERGY EFFICIENCY POLICY 147
    6.1. Evidence of Indirect Benefits 147
    6.2. Rebound Effects 148
    6.3. Net Impacts of Energy Efficiency Policies on Energy Use: Macro Evidence 150
    6.4. Distributional Effects 150
7. THE ROLE OF INNOVATION IN ENERGY EFFICIENCY 151
8. METHODOLOGICAL FRONTIERS IN ENERGY EFFICIENCY 152
    8.1. Frontiers in Energy Choice Modeling 152
    8.2. Frontiers in Energy Efficiency Program Evaluation 153

8.3. Frontiers in Estimating Sectoral and Economy-Wide Dynamics 154
9. CONCLUSIONS 154

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

1. INTRODUCTION

Energy efficiency features prominently in climate change forecasts, models, and policies. Research and policy have focused on how energy efficiency can help mitigate emissions of greenhouse gases and air and water pollutants and help reduce their attendant impacts on climate change and health (1–3). Despite its central role, significant uncertainty remains regarding how energy-efficient technologies, strategies, and policies affect economy-wide energy consumption and the dynamics that occur between the micro and the macro scales.

This journal has published several review articles on energy efficiency, typically focusing on specific contemporary issues. In the 1990s, the focus was on understanding the potential for specific energy technologies in the power sector and fuel cells (4, 5), as well as on the experience of implementing energy efficiency programs in countries like Russia, the United States, and Mexico (6–8). In the 2000s, focus shifted to understanding the implications of regulatory mechanisms in terms of end use benefits and links to rebound effects (3, 8, 9). In recent decades, research interest moved toward understanding economy-wide effects (8, 10), as well as the role of efficiency innovation (5, 11), and tracking the evolution of sectoral policies and regulations (9, 12).

This review covers four decades, spans a wide geography, and addresses a range of relevant topics. We describe the differences that have emerged as scholars from various disciplines have sought to answer specific questions using different definitions of energy efficiency, working at different levels of aggregation, and employing different theories and assumptions (Section 2). We assess what has been observed from historical trends (Section 3) in energy intensity, one of the most frequently used definitions and metrics to represent changes in energy efficiency, and we assess how energy intensity has influenced the understanding of energy requirements and policies. We then examine the policies used to encourage improved energy efficiency and to bridge the energy efficiency gap, and we explore the reasons why this gap persists (Section 4). We describe how policies evolved over time to drive efficiency improvements by energy users (Section 5), the outcomes of such policies (Section 6), and the unintended consequences that need policy attention. In Section 7, we summarize methodological advances for assessing energy efficiency outcomes. Finally, we offer in Section 8 some conclusions and suggest ways forward for future research. To accomplish this ambitious task of looking at energy efficiency from multiple different perspectives, our team includes energy efficiency researchers from 10 nations around the globe, each with a particular expertise and perspective to offer.

2. ENERGY EFFICIENCY DEFINED

There is no universal definition of energy efficiency, and the appropriate definition depends on the problem being considered as well as the context (13). At the most general level, we may define energy efficiency ε as the ratio of useful outputs (Q) to physical energy inputs (E) for a system ($\varepsilon = Q/E$) and energy intensity ($I = E/Q$) as the inverse of this measure.

The relevant system may vary in the outputs it provides (e.g., light, heat, work, wealth) and in its scale (e.g., a lightbulb, a machine tool, a firm, a sector, a national economy). Depending on the system and purpose at hand, it may be appropriate to use thermodynamic measures (e.g., enthalpy,

Q: useful outputs (e.g., lumens, passenger miles, GDP)

E: physical energy use (e.g., BTUs, Joules, GWh, Mtoes)

$\varepsilon = Q/E$: energy efficiency

$I = E/Q$: energy intensity

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

exergy), physical measures (e.g., vehicle kilometers, tons of steel, tons of oil), or economic measures [e.g., gross output, gross domestic product (GDP), expenditure on fuel] of inputs and outputs (13). Energy efficiency measures also differ in how they aggregate qualitatively different energy inputs (e.g., summing kilowatt-hours in a productive process such as a factory or weighting by relative price) (10, 14) and how they partition energy inputs between multiple and coproduced outputs (e.g., meat and wool) (15).

Physicists and engineers usually think of the energy efficiency of systems that transform energy or provide energy services in terms of first law and second law efficiencies. First law efficiency is the ratio of useful energy outputs to energy inputs. Second law efficiency considers the quality of energy inputs and outputs, or their ability to perform physical work (i.e., exergy). Second law efficiency is the ratio of useful exergy outputs to exergy inputs, and these measures allow the efficiency of a system to be compared to the theoretical maximum efficiency. As an example, a resistance heater has high first law efficiency but low second law efficiency—implying that it should be possible to obtain the same amount of heat at end user level with less energy input.

Economists distinguish between engineering or technical energy efficiency and economic energy efficiency. Economic energy efficiency controls for the levels of other inputs and considers cost-effectiveness and profit/utility maximization and the efficiency with which they are used. Engineering or technical efficiency compares the quantity of inputs, including energy, used to produce given outputs (or vice versa) to the best practice or frontier level and is one component of economic efficiency in general. Economists emphasize that improved energy efficiency is not necessarily the same as improved economic efficiency, since the latter considers, for example, all inputs, the costs of the inputs, and the mix of outputs. Macroeconomists often use an absolute measure, such as energy intensity or the ratio of primary or final energy consumption to GDP, as a proxy for the inverse of energy efficiency for a national economy. Although this is a simple and easily tractable metric, energy intensity is influenced by multiple variables.

The literature on energy efficiency often refers to the energy efficiency gap or paradox. Households and firms appear to underinvest in cost-effective energy efficiency technologies relative to what is privately or socially optimal. Physics- and engineering-based studies have, for a long time, estimated the difference between real and projected performance of energy efficiency deployment (16, 17). Another stream of literature has developed engineering efficiency cost curves that suggest that a considerable proportion of energy can be conserved at negative cost (3, 18–22) and that consumers and firms are not exploiting profitable investments. In these energy efficiency cost curves, researchers sometimes use different notions associated with the mitigation of the energy efficiency gap. That is, they consider either all available technological options that would be used to improve efficiency, regardless of their cost (i.e., the theoretical maximum engineering efficiency), or energy savings potential that could be achieved with net benefits to consumers (private economic gains) or with net benefits to society (societal economic gains or a gain in welfare) as well as the realistic or feasible potential, which is meant to present how much can be realistically achieved with policy interventions. Along the same lines, Jaffe & Stavins (23) propose two distinct notions. The technological optimum (or maximum) is achieved if all present barriers to adoption are eliminated, and the economic optimum refers to cost and addresses barriers that are market failures. Market failure can arise in the presence of public good features, or it can arise because of information asymmetry, a noncompetitive market, externalities not represented by the market price, or unexplained behavioral characteristics, just to name a few scenarios. Policy distortions, such as subsidies or incentives for some technologies or tax breaks for others, may also lead to the energy efficiency gap.

Others have built on this framework, with more recent work distinguishing between a private energy efficiency gap and a social energy efficiency gap (24). The private gap describes the

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

difference between current energy consumption and the energy consumption that would occur if all technologies or strategies that have a positive net benefit (net present value, annualized net benefits, or similar metrics) were pursued. The social gap also explicitly includes benefits associated with having energy service markets working closer to ideal conditions, and it also includes the avoided negative externalities associated with energy usage that are not reflected in energy prices (25).

Estimates of the energy efficiency gap (i.e., the difference in energy consumption between what is currently observed and what energy consumption would be if the most efficient technologies were adopted), though imperfect, have proved extremely useful as a guide to research and development (R&D) and policy design.

At the level of countries, macroeconomists often use the inverse of energy intensity (the ratio of primary or final energy consumption to GDP) as a proxy for energy efficiency for a national economy. Although this is a simple and easily tractable metric, energy intensity is influenced by multiple variables. Energy intensity has declined, but not as rapidly as modelers at the International Energy Agency (IEA) and other organizations have predicted (26).

Macroeconomists use decomposition analysis, a method that identifies the relative contribution of different factors and changes therein to changes in energy intensity at the sector or economy-wide level. These changes may be impacted by the variation of final consumption structure, technical efficiency of production, intermediate input structure, policy, and consumer preferences. This in turn leads to the construction of composite energy intensity indices from the weighted sum of the energy intensities of lower-level sectors (27). These indices are widely used to assess progress against national energy efficiency targets (27–29) but differ in their choice of decomposition factors, sectors, output measures, and decomposition techniques (27), making it difficult to perform geographic or country-level comparisons.

Economists can decompose the effect of changes in inputs and technology on economic output using a production function of the form $Q = \lambda f(\pi K, \rho L, \tau E, \upsilon M)$ (30), where Q represents real physical output ($Q = Y/P$, where Y is nominal GDP and P is the GDP price deflator) and K, L, E, and M are capital, labor, energy, and material inputs, respectively. λ, π, ρ, τ, and υ are time-dependent multipliers representing technical change. The index of energy-augmenting technical change, τ, measures the productivity specifically associated with using energy. Specifically, if energy use fell by 1% while all other inputs and their multipliers were held constant and output did not decline, then there would be 1% of energy-augmenting technical change (30). Hence, because less energy is required to produce the same level of output, this should reduce aggregate energy intensity ($I = E/Y$), ceteris paribus. Energy-augmenting technical change (τ) provides one measure of energy efficiency improvement but is difficult to estimate empirically (31). In contrast, it is straightforward to measure the aggregate energy efficiency of a sector ($\varepsilon = Q/E$), but this relationship depends on the level and price of each input [(unit) cost], the current state of technology, and the level of output, as well as on how individual inputs are measured and aggregated. In addition, a one-off or ongoing improvement in the productivity of energy inputs (τ) will lower the price of effective energy (τE) and hence encourage producers to substitute (effective) energy for other inputs (9). As a result, a 1% improvement in the productivity of energy inputs (τ) within a firm, sector, or economy may not translate to a 1% improvement in the aggregate energy efficiency (ε) of that firm, sector, or economy. Also, changes in aggregate energy efficiency may result from changes in the level, price, and productivity of nonenergy inputs, even in the absence of energy-augmenting technical change. Similarly, improvements in energy efficiency at one level of aggregation (e.g., an industrial sector) may not translate to the same improvements in energy efficiency at a higher level of aggregation (e.g., a national economy) owing to a variety of macroeconomic adjustments, such as a shift toward more energy-intensive goods and services due to a fall in their relative price.

$Q = \lambda f(\pi K, \rho L, \tau E, \upsilon M)$: production function, where Q represents real physical output; K, L, E, and M are capital, labor, energy, and material inputs, respectively; and λ, π, ρ, τ, and υ are exogenous, time-dependent multipliers representing technical change

Y: real economic output (often real GDP)

$I = E/Y$: energy intensity

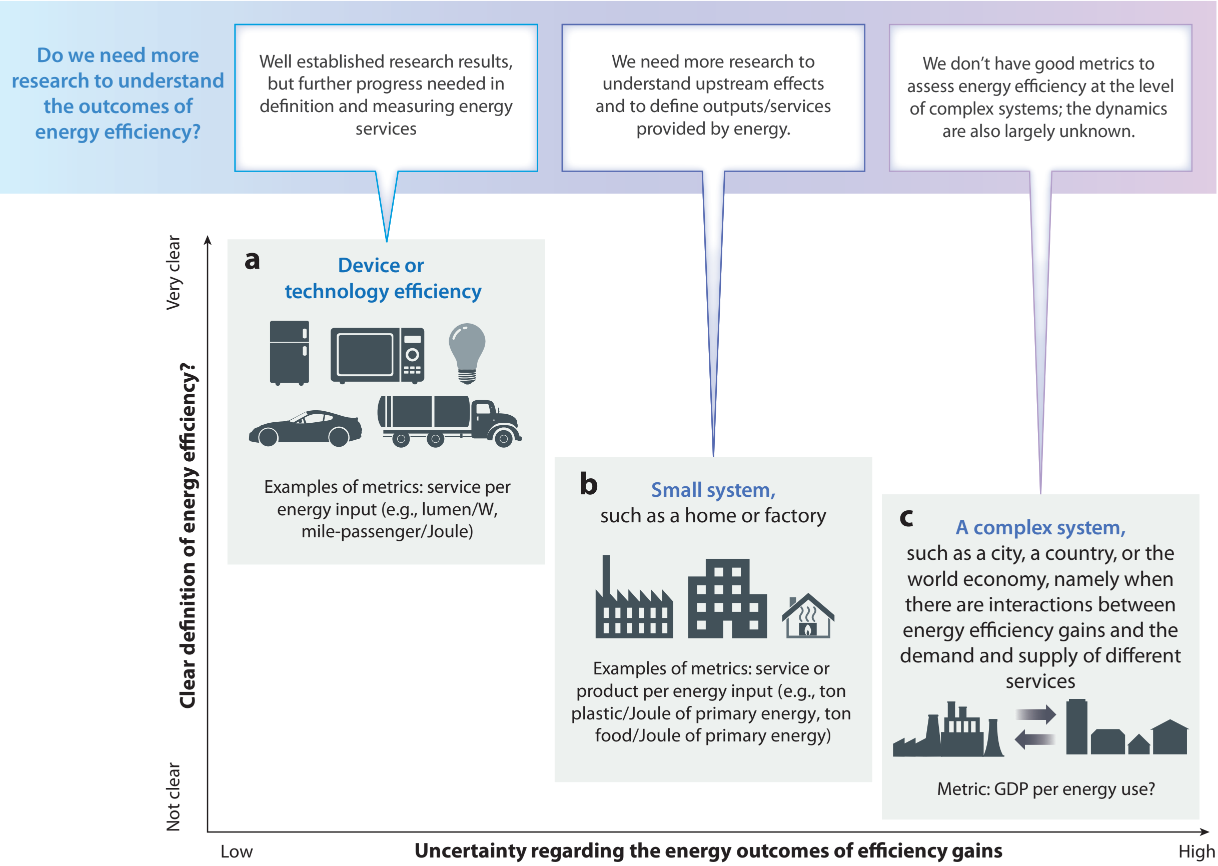

Figure 1

This figure illustrates domains of energy efficiency research and highlights whether the definition of energy efficiency and the metrics to assess energy efficiency outcomes and their levels of uncertainty are well specified. The vertical axis identifies whether there is a clear definition of efficiency for that scope, and the horizontal axis illustrates the level of uncertainty regarding the outcomes of energy efficiency. Whereas at the device/appliance level there is an abundance of studies and broad understanding of what efficiency means and how to measure it (illustrated in panel *a*), the concept and metrics for energy efficiency become more difficult to define as systems boundaries increase and become more complex, which also leads to more uncertainty regarding the outcome of energy efficiency (panels *b* and *c*). Larger and more complex systems, such as homes, factories, and regions (panel *b*), are prone to high uncertainty regarding energy efficiency outcomes. Furthermore, for complex systems such as cities, regions, and countries (panel *c*), appropriate metrics to understand the level of efficiency are missing.

In sum, the links between improvements in one measure of energy efficiency (e.g., τE) and improvements in another measure (e.g., ε) at either the same or different levels of aggregation are complicated. Analysts and policy makers must take care when comparing and interpreting their results, avoiding apples-to-oranges comparisons.

Figure 1 summarizes the domains of where the definition and metrics for energy efficiency may be more or less clear, and more or less uncertain. Whereas at the device/appliance level there are plenty of studies and broad understanding of what efficiency means and how to measure it, the concept and metrics for energy efficiency become more difficult to define as systems boundaries increase and become more complex. This also leads to more uncertainty regarding the outcome

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

of energy efficiency. Different definitions, if inappropriately applied, can lead to erroneous interpretations of outcomes of interest. At larger system levels, such as homes, factories, or a region, uncertainty prevails. Furthermore, for complex systems such as cities, regions, or countries, appropriate metrics to understand the level of efficiency are missing.

3. HISTORICAL TRENDS

Energy intensity trends, owing to their simplicity, have been widely used to represent progress in energy efficiency for practical policy purposes and decision making (e.g., 32). Energy intensity is, nevertheless, a crude and highly imperfect measure of energy efficiency. Despite such limitations, energy intensity estimates have provided valuable insights into the evolution of understanding energy requirements at different stages of economic development, across sectors and countries. Early studies introduced the stylized fact of the inverted-U-shaped curve of energy intensities in the long run (33). As shown in **Figure 2*a*,*b***, energy intensity appears to rise with industrialization and then decline.

The variations in energy intensity over time reflect the changes in the demand for energy services as an economy develops (40), including the effect of changing economic structure and demand for more and less energy-intensive goods. Changes in energy intensity also reflect the efficiency with which these services are provided as well as geographical and climatic conditions (41). In particular, industrializing economies are likely to experience substantial increases in the demand for energy services as they develop—first for industrial heating and then for industrial power and freight transport as the production side of the economy expands (38).

One limitation of studies of energy intensity of the economy has been the lack of data on traditional energy sources, such as wood fuel, charcoal, dung, and animal power. The economies depicted in **Figure 2*a*** suffer from this limitation, whereas the economies depicted in **Figure 2*b*,*c*** do not. Thus, a richer story emerges in which certain economies, such as the United Kingdom and Germany, which benefited from large coal deposits but had limited traditional energy sources, experienced inverted-U-shaped trends. Other economies with abundant traditional energy sources, including the United States, Sweden, and Brazil, followed declining trends. **Figure 2*a*** highlights the rapid rise in the fossil fuel energy intensity of industrializing economies, such as China and India (41). From early on, scholars have attempted to untangle the connection between energy use and economic growth and how efficiency gains affect that connection. Technological change rather than broad structural change within industries appears to be responsible for more of the decline in energy intensity globally (26); for example, the UK economy saw an approximate 30-fold increase in steam engine efficiency from 1750 to 1850 and a further approximate 5-fold increase in efficiency through to 1970. In the absence of consumption-based accounting, declining energy intensity can also be influenced by importing energy-intensive goods from industrializing economies (42).

Figure 2*c* shows a rising trend in per-capita energy consumption with apparent saturation post-1970s, except for Brazil. Although it may be tempting to attribute this tendency to sharply rising oil prices in the mid-1970s and early 1980s, saturation has continued after oil prices declined. Its absence in Brazil may point to per-capita consumption reflecting trends in energy intensity as economies develop.

Over the last few decades, the variation in energy intensities [in gigajoule (GJ)/GDP] across some regions and countries is narrowing (43, 44) (see also **Figure 2*a*,*b***); this convergence has taken approximately a century since 1850. Economies tend to broadly converge at high levels of per-capita income, and reductions in energy intensity occur in tandem with increases

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

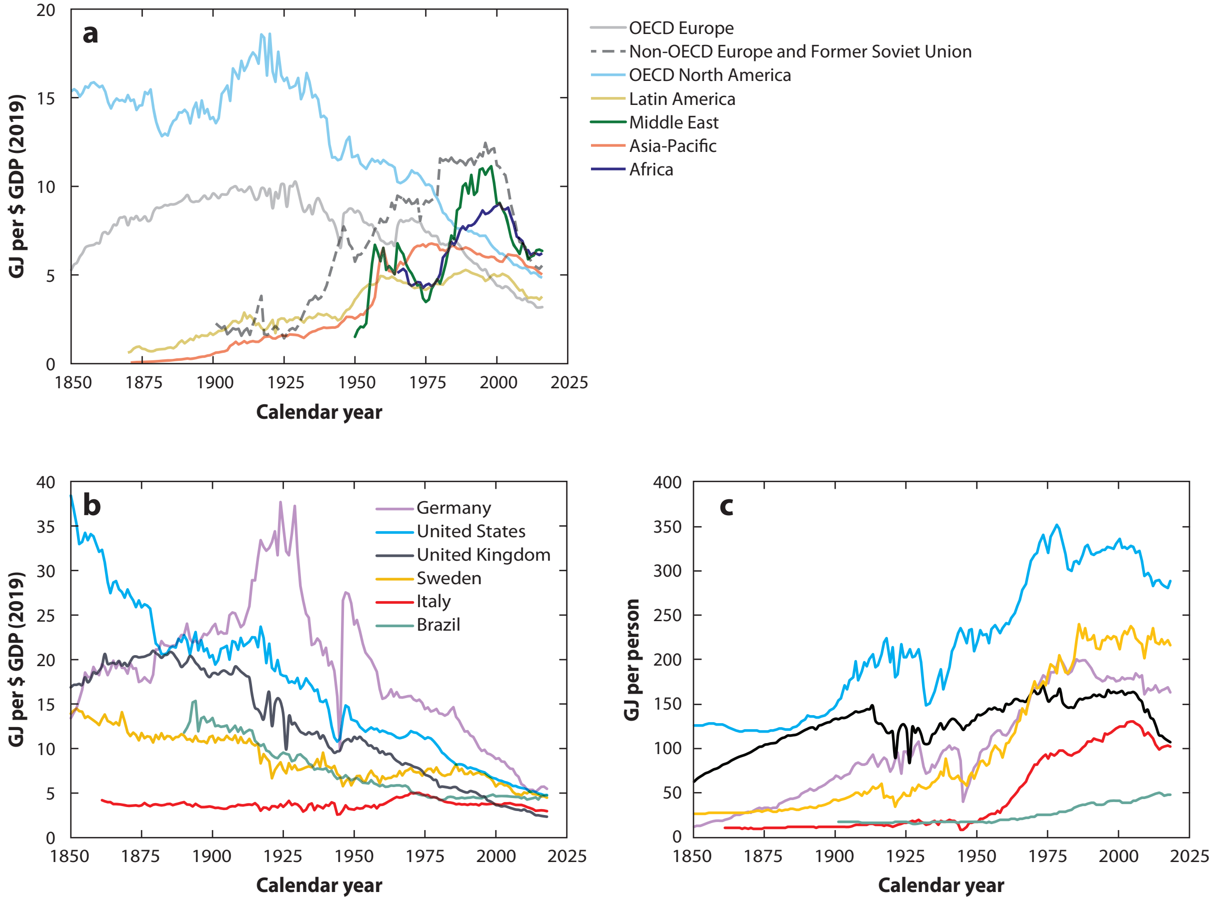

Figure 2

(*a*) Energy intensity for regions of the world, including only modern energy sources and excluding traditional energy sources (1850–2016). (*b*) Energy intensity for major economies, including traditional and modern energy sources (1850–2016). (*c*) Energy consumption per capita for major economies, including traditional and modern energy sources (1850–2016). All dollar figures have been converted to real 2019 dollars. Energy is primary energy. Figure produced by the authors using data sources (34–39). Abbreviations: GDP, gross domestic product; GJ, gigajoule; OECD, Organisation for Economic Co-operation and Development.

in GDP (35). This convergence reflects that many global economies are in the process of industrializing (using an energy-intensive model of economic development) or have industrialized (finding more efficient ways of producing economic value).

Examining energy intensity across countries at similar levels of GDP, van Benthem (45) finds that today's developing economies are more energy intensive than present-day Organisation for Economic Co-operation and Development (OECD) countries when they were at similar levels of economic development. The author breaks down the factors into more efficient technologies today, more exporting in developing economies today, and consuming more energy-intensive bundles today, and finds that the last two factors outweigh the first (45).

Meanwhile, Hart (46) asks why global energy intensity has fallen only modestly over the last 150 years despite substantial improvements in the (physical) energy efficiency of numerous individual production processes over the same period. This leads him to consider to what degree

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

the shift to more energy-intensive consumption has been driven by income effects (it just happens that more luxurious goods are also more energy intensive) or by substitution effects so that increased energy efficiency has resulted in substitution toward more energy-intensive goods—a rebound effect. On the basis of this analysis, Hart finds that the rebound effect is responsible for 50% of the gap between the change in energy intensity and the change in energy efficiency and that the remaining gap is explained by income effects encouraging consumption patterns to shift over time toward more energy-intensive goods.

In summary, a key lesson from a historical perspective is that energy intensity trends depend on the state of economic development, certainly declining at higher levels. Across economies, there are signs of strong convergence in energy intensity and limited convergence in per-capita energy consumption. This, in part, reflects the differing trends in the energy intensity metric and energy per capita metric. Whereas energy intensity has declined over 170 years by a factor of 3 to 8 across countries, per-capita energy use has gone up by a factor of ~5 over 150 years in OECD countries, despite tremendous energy efficiency gains.

4. THE ENERGY EFFICIENCY GAP AND GROUNDS FOR POLICY INTERVENTION

Some researchers raise the issue of whether energy efficiency policies restrict consumer choices, potentially reducing social welfare, given that if energy efficiency technologies were the optimal solution, consumers would have already taken advantage of them (47). Others claim that market failures warrant policy intervention (3, 19, 20). Market failures include all the "feature(s) of the energy services market that are believed to inhibit investment in energy efficiency" (48, p. 9). These include misplaced incentives (49), imperfect information (49, 50), decisions influenced by habit and nonperfect substitutability (49), negative externalities (26, 50), bounded rationality (50), uncertainty (49), transaction costs (49, 50), and lack of access to financing (48, 49).

Several failures, which could be summarized as nonmarket failures or disincentives to adoption, specific market failures, and unexplained behavioral characteristics, have been proposed in the literature (51). Nonmarket failures include consumer heterogeneity, uncertainty relating to product performance and future energy prices, unobserved costs and benefits, and rebound (3). In particular, there has been much questioning within the economics literature about the engineering cost estimates of potential savings, with convincing evidence suggesting that realized savings can be significantly lower than expected (3, 52). Other arguments point toward hassle costs that, though convincing, are likely to be context specific (53). Efficiency adopters may use significantly different discount rates. We would argue that more evidence is needed on the extent to which consumer heterogeneity is a factor and on the longer-term persistence of savings and product performance.

The subset of barriers that some economists would consider market failures can be summarized as comprising energy market failures (e.g., unpriced environmental externalities and average-cost pricing), information market failures (e.g., asymmetric information and principal-agent problems), capital market failures (e.g., credit constraints), and innovation market failures (e.g., arising from R&D spillovers, in which innovating firms cannot capture the full benefits of their efforts) (16, 52). Although evidence of certain market failures is persuasive, specifically regarding information market failures (54, 55), more work is needed to quantify the potential energy savings from addressing them.

Driven by applications of behavioral economics and environmental psychology to studies of energy use, growing attention has been given to behavioral factors that can also help explain the energy efficiency gap. In particular, there has been increasing interest in the analysis of unexplained

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

behavioral characteristics (sometimes called anomalies or irrationalities) that potentially prevent energy users from behaving as the rational theory model would predict (24, 56, 57). Consistent with the economists' optimum, this approach assumes market agents with well-defined preferences that use all available information make rational choices to maximize utility with perfect foresight and impeccable optimization skills under budget constraints.

Within the context of energy efficiency, behavioral economics studies have revealed a variety of behaviors that can potentially explain the gap. Randomized controlled trials (RCTs), which are powerful tools for identifying causal effects, have shown how these divergences can drive individuals to behave in a way that leads to suboptimal choices in energy efficiency and conservation activities. That is, when behavioral differences lead to a systematic difference between decision utility (i.e., expected or intended utility at the time of choice) and experienced utility (i.e., utility experienced after the choice) (57), there seems to be conceptual agreement that they should be labeled as failures, which in turn provides additional rationales for energy efficiency policy (56). However, much more empirical research is needed to determine whether unexplained anomalies do in fact cause systematic deviations between decision utility and experienced utility—and, furthermore, whether they systematically contribute to a neglect of energy efficiency opportunities (11, 19)—and, even more importantly, to ensure the validity of metrics used in such analysis.

An interdisciplinary approach to the energy efficiency gap is warranted to ascribe the gap to its cause and delineate effective mechanisms to deal with it. For example, there is little point in attempting to use behavior change or price mechanisms to reduce unexpectedly high heat demand if the problem is actually the result of poorly constructed houses. Given the heterogeneity of behaviors, motives, and market and policy conditions, we argue that behavioral factors explaining the gap and resulting policy interventions will need to be context specific. Wilson & Dowlatabadi (58) expand the somewhat siloed thinking on energy efficiency and consumer decision making by presenting a range of frameworks, from neoclassical and behavioral economics to technology adoption models and sociotechnical frameworks, in which technology adoption is determined by broader technical and cultural factors. Relatedly, the innovation diffusion literature suggests that economically and technically superior technologies are not typically immediately adopted and tend to follow a sigmoid or S-shaped diffusion curve. The diffusion process is a complex combination of barriers and drivers reflecting the difficulties of taking a new technology to the marketplace.

Overall, there is strong support in the literature to conclude that market barriers, market failures, behavioral failures, negative externalities, and issues of culture and norms justify policy intervention to improve energy efficiency.

5. POLICIES USED TO IMPROVE ENERGY EFFICIENCY

5.1. Types of Policies

Over the last four decades several types of policies to improve energy efficiency and conservation have evolved, have been implemented, and have been scaled up across countries and regions. In this context, the policy assessment literature has grown considerably, particularly in industrialized countries and in some developing country contexts as well. Owing to page limitations, we summarize in the subsections below the existing knowledge for both traditional policies (e.g., efficiency standards, information and labeling programs) and relatively new, more recent behavior-oriented interventions (e.g., social norms, rewards).

5.1.1. Appliance and equipment efficiency standards and building codes. The most widely used policy over the last four decades has been energy efficiency standards for appliances and equipment (59). Standards have been adopted in the United States since the 1970s (59, 60), beginning with California and New York, with US national voluntary standards, and later mandatory standards following suit (58, 59). Similar appliance standards and building codes have been pursued in many other countries and regions, and the need for scale-up and expansion of the scope is reflected in the literature for the European Union (61), China (62), and India (63) and has become pervasive globally (64). Some studies find that efficiency standards might decrease production costs to manufacturers, resulting in lower retail prices (see, e.g., 65 regarding standards for refrigerators in the United States), whereas other studies show an increase in prices (e.g., 66), though a lower increase than previously anticipated. Grubb et al. (67) find that demand-pull forces unquestionably played an important role in improving vehicle efficiency but were in tension with and substantially offset by other factors, including vehicle mass, engine power, acceleration, and occupant safety. However, the relative contribution of prices versus standards in econometric studies depends on the period, study design, and region (e.g., contrast 68 with 69). Newell et al. (70) found energy efficiency regulations in the United States induced energy efficiency improvements exceeding 7% for room air conditioners and water heaters (1973–1993). They found little improvement in cost, in contrast to Wei et al. (71), who found improved energy efficiency in lighting and various appliances to be strongly correlated to the introduction of energy efficiency standards, without a noticeable cost penalty. It is interesting to note that most studies criticizing the (cost-)effectiveness of appliance standards provide theoretical arguments but lack empirics (60).

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

5.1.2. Information and labeling. Information, consumer awareness campaigns, and labeling of products provide information to consumers to enable better decision making. Some of these strategies, such as the Energy Star labeling program run by the US Environmental Protection Agency (EPA), have had a big impact for some products (60) but are also now popular in almost all countries. Newell et al. (70) found that labeling requirements, combined with higher energy prices, encourage the production of more energy-efficient products.

5.1.3. Economic incentives. The literature on financial and economic mechanisms to encourage energy efficiency is vast and includes subsidies, loans, taxes, rebates, performance contracting, on-bill financing schemes, and tradable certificates. At the risk of oversimplification, studies show there is an abundance of economic incentives already implemented (e.g., subsidies) (72). The evidence is mixed and their (cost-)effectiveness varies and is subject to numerous conditions (e.g., energy pricing, targeted fuels, income, direct rebound effects, scale of market failures) (e.g., 24, 54, 61, 73–75). Most often, studies deal with the evaluation of a single instrument, so uncertainties and limitations related to the interaction with the policy mix have been ignored. There is also a need for more ex post evaluations to assert, among other issues, whether ex ante estimates of cost and energy savings are overestimated (76).

5.1.4. Providing feedback to consumers. The advent of advanced metering infrastructure in the last decade enabled consumers to have regular and detailed information about energy consumption. However, researchers found that consumers were confused about what smart meters and their functionalities were as advanced metering infrastructure was expanding (77). The provision of direct feedback has long been used by utilities and authorities to promote energy efficiency, with mixed results. Studies show that households that received continuous, weekly, or daily feedback (e.g., via smart metering) saved more energy than those that received no information (78, 79), including the provision of loss-framed salient information (80). In some instances, households that received feedback on energy consumption by appliance still had serious misconceptions about their energy use (81). Furthermore, providing information or feedback may not lead to behavior change or the adoption of efficient technologies (82), which questions its persistence in the long term as a policy option. For instance, Buchanan et al. (83) found limited evidence of feedback effectiveness and identified user engagement as a critical factor. Feedback also has the potential to shift peak consumption to off-peak periods (but of course this would not necessarily lead to a decrease in energy use) (64).

Another form of feedback is the use of social norms, which refers to providing users with information about their energy consumption when compared with best-performing households or average use of similar households (62). The evidence shows that the use of social norms is (cost-)effective at promoting energy efficiency and conservation, with savings ranging from 1% to 30% (84, 85). However, various critical issues remain to be investigated, including potential rebound, boomerang, and moral licensing effects (whereby agents departing from supposedly normally accepted behavior move toward the associated peer group norm) (85–87).

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

5.1.5. Pledges or commitments. These pledges or commitments promise to change behavior (88) related to energy use, whereby individuals lock themselves today to actions they will take in the future (89). Some studies have identified a significant effectiveness, particularly if the commitment and related goal are realistically self-imposed (90). However, other initiatives show the opposite outcome or reach insignificant results (91).

5.1.6. Rewards. Rewards include strategies such as prizes, rebates, and tax credits. Studies show significant effects when reward mechanisms are in place (92, 93), and underline the importance of feedback as a supportive measure for rewards to be effective (94). Some studies show that financial rewards appear to have a positive effect on reducing consumption (95). However, the literature highlights methodological issues, including confounding of effects (given that most studies combine different interventions) and intrinsic biases due to evaluated samples with highly motivated participants (88).

Several (meta-)analyses show that policy interventions have a positive impact on reducing energy demand (96, 97), even when free riding and rebound effects are considered (76). Estimates for energy reduction range from 3% to 20%, but with results being highly context dependent (54). Policy distortions or failures (such as the lack of policy action, subsidies, incentives, or taxes for nonefficient energy strategies) can also affect the outcomes. Policy complementarities and the level of ambition (e.g., via stringent energy savings targets) appear to be critical determinants for significant impacts.

5.2. Evidence of Direct Benefits

Assessing the impact of policies on outcomes, or attribution, is complicated by several factors, including the need to estimate a counterfactual (what would have happened otherwise). This attribution is easiest when the assessment is done at the product level (see **Figure 1**).

Numerous studies find that energy reduction is associated with energy efficiency labels and efficiency standards for household appliances, lighting, building efficiency, vehicles, and motor drives. For example, the Energy Star labeling program run by the EPA has had a big impact for some products (60). In a review of eight categories of policies for energy efficiency in buildings, covering about 44 assessments (98), standards and labels dominated the policies estimated to save more than 100 TWh (lifetime impact). However, the diversity of sources, including ex ante regulatory impact analyses, means the underlying methodologies are varied.

When assessing the outcomes of several energy efficiency programs (including building codes, product standards, subsidies, information provision and weatherization, and behavioral interventions), Gillingham et al. (54) found that estimated energy savings range from 0 to 24% of baseline consumption, with considerable variation depending on the type of intervention. Reported savings from voluntary agreements across Europe similarly vary widely (99). Ex post econometric evaluations of instruments targeted at business and public sector energy use in the United Kingdom find significant savings: The climate change levy and related climate change agreements demonstrated an announcement effect, with more enduring induced energy savings of approximately 5% per year (100), while the Carbon Reduction Commitment (CRC) energy efficiency scheme, which required organizations to report and buy allowances to cover their direct and indirect emissions, reduced CO_2 emissions by 6–8% (with gas savings greater than electricity savings), approximately three times the ex ante estimate, probably because of the way it combined economic and noneconomic incentives (101).

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

5.3. Cost-Effectiveness of Energy Efficiency Programs

Cost-effectiveness ranges from 1.1 cent for behavioral programs to 50 cents and higher per kilowatt-hour (both in 2015 USD) for some subsidy programs (75). Some of these interventions are not cost-effective when compared to the price of energy. The review by Boza-Kiss et al. (98) also finds wide variation, with cost savings mostly in the range of 1 to 6 USc/kWh in western Europe and the United States, but often over 10 USc/kWh in eastern European countries. Bento et al. (102) find that certain vehicle efficiency standards provide benefits exceeding costs. Measured cost-effectiveness can be lower for low-income households (103), but recent work has confirmed that rebound can also be stronger for those households (104, 105). Energy savings from similar measures can also vary significantly depending on income and household deprivation, with lower-income households saving less (106) but likely receiving other nonmeasured benefits. These results emphasize that any welfare calculation is incomplete unless a wide set of benefits are considered.

6. WIDER CONSEQUENCES OF ENERGY EFFICIENCY POLICY

In Section 5 we defined different types of energy efficiency policies and their direct benefits and cost-effectiveness. Here, we discuss the wider consequences of energy efficiency in terms of its indirect benefits, rebound effects, the relationship between energy efficiency policies and welfare, and distributional issues.

6.1. Evidence of Indirect Benefits

Many authors have attempted to estimate the nonenergy benefits of energy efficiency (61, 107). Ürge-Vorsatz et al. (61) categorize these benefits as comprising health effects, ecological effects, economic effects, service provision benefits, and social effects, and the Intergovernmental Panel on Climate Change (IPCC) (108) shows energy efficiency synergies with Sustainable Development Goals (SDGs) of the United Nations. An IEA study identified 15 major social welfare–creating outcomes that are, or may be, beneficiaries of energy efficiency improvements (107). These include increased employment, access to affordable energy, reduced ground-level emissions, and reductions in negative energy trade balances. Similarly, de la Rue du Can et al. (109) show that energy efficiency policy in Ghana could lead to significantly expanded energy access. We would argue that quantifying indirect benefits is difficult, and much more work needs to be undertaken to improve quantification of these indirect benefits.

As energy efficiency policies, strategies, and technologies are pursued, there may be cobenefits in the form of reducing negative externalities. For example, if an efficiency measure reduces the use of fossil fuels, there will be cobenefits from such a measure in the form of reduced climate change impacts from greenhouse gases and reduced health damages associated with ground-level emissions of air pollutants (3, 110, 111).

Using a microeconomic framework, Chan & Gillingham (18) demonstrate the conditions under which energy efficiency is welfare enhancing. Azevedo (3) takes a broader perspective, calling for a multiobjective perspective that should include emissions consequences, costs, and changes in overall welfare. The costs and benefits of energy efficiency programs have been debated extensively (23, 24, 58, 59). Whether energy efficiency is estimated to be welfare enhancing can depend on multiple factors, including the type of policy intervention, the target population, the substitutability/complementarity of energy and other services, how broadly one considers welfare, whether cost-effectiveness includes estimates of the social cost of carbon (51, 53, 54, 112), and the cobenefits or costs induced by changes in externalities. It has proven difficult to measure the costs and benefits in a comprehensive manner, as they vary widely depending on multiple factors and contexts, and data availability varies considerably across geographies. Fouquet (55) shows that in the United Kingdom, consumer surplus rose substantially during key energy transitions involving energy efficiency.

One geography with good data is the United States, and for this reason much of the previously published academic work has been conducted there (57). Gillingham et al. (54) estimate an aggregated net saving of 2.8 USc/kWh from energy efficiency, which compares favorably to the marginal social cost of electricity generation, estimated at 5.6 USc/kWh (both in 2015 USD). Billingsley et al. (103) compile data on over 1,700 programs reported to US state regulators from 2009 to 2011 and find the average levelized cost for energy savings to be 2.1 USc/kWh (in 2012 USD), with significant cross-sectoral variation (105). Meanwhile in Europe, several studies have estimated the cost per kilowatt-hour saved to range from 0.4 to 1.1 (euro) cents (in 2008–2015 EUR) (24).

6.2. Rebound Effects

A notable development over the last 40 years has been the persistently reemerging debate on rebound effects. Rebound effects can be thought of as functioning like a price mechanism—efficiency gains reduce the effective price seen by users by increasing the energy services provided by a unit of energy—so they tend to increase physical energy use above what simple engineering calculations would predict (112). Coupled with this, energy efficiency gains can spur the development of new energy-using technologies and increase disposable income and profitable production output, dragging up energy demand. There are other flow-on effects that affect energy use and rebound across the economy. First mentioned by Jevons (113) in 1865, and then resurrected in the literature by Brookes (114) and Khazzoom (112) in the 1970s, rebound effects were then studied by Grubb (115), Saunders (116), Pearson & Fouquet (117), Roy (118), and Lowe (119), as well as many other contributors who can be found in the seminal volume edited by Schipper (120). More recent contributions arose from Azevedo (3), Gillingham et al. (121), Saunders (30, 122, 123), Sorrell (124, 125), Stern (126), and Santarius et al. (127).

Rebound effects can be described as direct, indirect, and economy wide. Direct rebound effects are those directly related to the use of physical energy itself at the end point. Indirect rebound effects are those due to end users shifting their consumption of energy embedded in consumption goods and services that result from different consumption patterns or switching energy use among different fuels. Indirect rebound effects are also due to resulting shifts by producers among inputs, including physical energy (125). Economy-wide rebound effects refer to all adjustments in prices and consumption that lead to a new equilibrium price and quantity for different sectors of the economy as an efficiency improvement occurs. Santarius et al. (127) extended the taxonomy to consider meso rebound effects, which link micro effects to macro (economy-wide) effects through multiple levels, finding rebounds ranging from 0 to more than 300% in some studies.

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Researchers have reached different conclusions regarding the magnitude of rebound effects, in part given the different scope of analysis, the efficiency metric used, whether long-term effects are captured, or whether referring to consumers with less access and affordability, among many other differences. Some studies find small-to-moderate rebound effects (128), whereas others show large rebound effects (and in a few cases even backfire) (3, 111, 124, 129–131) and others show super conservation (negative rebound) (130). While rebound increases energy use, under most conditions, it also increases economic welfare (116), excluding externalities.

There is some evidence that rebound magnitude is higher on the production side (30) than on the end use side. Globally, the production of goods accounts for two-thirds of the global economy's energy use (123).

Different model structures and specifications (and the different scopes of analysis they entail) lead to different rebound projections arising from energy efficiency gains, as they are in fact referent to quite different issues. Azevedo (3) showed how ease of substitution by consumers across energy and nonenergy goods (own- and cross-price elasticities) drives rebound, echoing Druckman et al. (131). Functional forms in common use today in integrated assessment models range from Leontief-like (fixed factors) to Cobb-Douglas to constant elasticity of substitution forms, with the last being the most flexible and general approach. However, that comes at a cost, as the assumed substitution elasticities are uncertain and they will strongly drive rebound (116, 122, 123). Saunders provides more general functions (30, 122), but those are currently impractical in most settings owing to (global) data limitations (123).

Long-term economy-wide rebound studies under a macroeconomic framework using general equilibrium models have generally concluded that large rebound effects occur in the long term (126, 132–135). The elasticity (ease) of substitution between energy and other inputs is a key determinant of long-term rebound on the productive side (30, 116, 125). Pearson & Fouquet (117) propose that the resolution of the Jevons paradox is to appreciate that rebound effects vary at different levels of economic development and that rebound magnitudes at early stages of development are likely to present as backfire. These macroeconomic studies often use energy intensity as a proxy for energy efficiency. Stern (26), in a study across 87 countries and over 37 years, showed that when energy efficiency is understood as a technology gain, the effects on energy intensity are complex and magnitudes and dynamics differ between the two metrics. Energy intensity has declined, but not as rapidly as modelers at the IEA and other organizations have predicted (136), owing perhaps to underestimates of rebound effects, which Stern (126) shows may approach 100% economy wide, leading to overestimates of savings. Brockway et al. (137) undertake a broad review of the evidence and find that economy-wide rebound effects may erode more than half of the expected energy savings from improved energy efficiency. They conclude that global energy scenarios may underestimate the future rate of growth of global energy demand. Wei et al. (138) describe the importance of considering the trends of other inputs to production and their impacts on both output and energy use when observing energy intensity trends. Nonenergy technology gains matter: Nonenergy technology gains could also have important effects on energy intensity (26, 30), effects not captured in many models used for projecting energy use trends that drive emissions projections (123).

In summary, better understanding of the wider impacts of user reactions to energy efficiency may call for refraining from grouping all these effects under one homogeneous category of rebound and instead identify them by the processes and contexts giving rise to them. Although in some cases rebound-suppressing policies will be helpful in realizing reduced energy use from energy efficiency programs, in other cases a wider impact of providing affordable access to energy might appropriately cause policy makers to sacrifice some potential for energy use reduction from

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

technology deployment in favor of affordable access and a minimum level of per-capita energy consumption, especially in developing countries (112).

6.3. Net Impacts of Energy Efficiency Policies on Energy Use: Macro Evidence

Evaluating the impact of energy efficiency and related policies on actual energy consumption presents a challenge: determining what would have happened in the absence of the policy (i.e., what is the counterfactual). A comparison across regions seems indicative that the trend of global energy efficiency (using energy intensity as its proxy, with all the caveats already described in Sections 2 and 3) has accelerated somewhat since the early to mid-2000s, in parallel with both rising energy prices and a rapid expansion of energy policies associated with rising climate change concerns and international commitments (139). The decomposition analysis in Reference 139, consistent with much other data, makes it clear that at least three-quarters of these emission savings were due to energy intensity improvements rather than to decarbonizing energy supply.

Since 2010, energy intensity and total carbon emissions have declined most sharply in countries that had adopted a wide raft of strengthened policies on energy efficiency across all sectors (140). Lamb et al. (139) showed this occurred across all sectors for all regions of the world. Indeed, Maamoun (141), using extensive econometric analysis, showed how participating in the Kyoto Protocol led to an average increase in national CO_2 reductions of 7%.

6.4. Distributional Effects

Historically, energy intensity seemed to depend on the stage of economic development. Unless the energy is supplied from carbon-free sources, the greenhouse gas emissions intensity will also be higher at early stages of development. Developing countries, as did industrialized countries in their early development, require more energy to increase their living standards to industrialized country levels as they build the infrastructure of modernity. This exposes an ethical trade-off between economic well-being and climate change mitigation. The trade-off for rich and poorer countries is different. In addition, under conditions where rebound effects occur, economic welfare will increase faster but at the expense of the resulting energy use being above where it would be in the absence of rebound effects. This complicates the task of policy makers. As noted by the IPCC (108, p. 16), in scenario P1, "social, business and technological innovations result in lower energy demand up to 2050 while living standards rise especially in the global south." The report also mentions that "mitigation actions in energy-demand sectors and behavioural response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions" (108, p. 157). In developing countries, rebound-suppressing policies cannot help achieve affordable access to energy (Strategic Development Goal SDG 7 – 'Affordable and Clean Energy') faster, so rebound-suppressing policies can disproportionately harm consumers [experiencing] energy poverty (129).

Regions, countries, and communities with unmet/unsatiated energy demand will see absolute energy use grow even as energy efficiency technologies and policies are deployed. This makes the deployment of cost-effective noncarbon energy sources more urgent. Within countries, lower income quintiles generally appear to have higher energy intensities—higher energy per unit income—even in industrialized world settings (142).

In summary, careful implementation based on lessons learned from cross-country experiences is needed. More work is also needed to reconcile disparities between predicted and actual savings and net benefits. RCTs, which are powerful tools for identifying potential causal relationships, have shown how these divergences can drive individuals to make apparently suboptimal

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

choices in energy efficiency and energy conservation activities (143). To further build the needed evidence base and to better understand the factors that affect energy efficiency outcomes, we need improved synthesis of multiple RCTs and other empirical methods through the use of more systematic reviews, case studies, replication, and meta-analyses.

7. THE ROLE OF INNOVATION IN ENERGY EFFICIENCY

There is no question that the productivity of energy consumption relative to the service provision has improved greatly. These improvements in energy services with new or more efficient technologies are due to innovation. Lighting, which has seen a 10,000-fold improvement in lumens per watt since the onset of the Industrial Revolution, is perhaps the most dramatic and famous example (40). Innovation can be exogenous (discovery or spilling over from innovations elsewhere) or driven by focused public R&D, but a substantial portion of energy efficiency innovation is induced by demand-pull forces (policies or prices). By the mid-1980s, Lichtenberg (144) had found that energy price increases induced innovation for both producers and end use consumers.

Aside from lighting, large technical improvements in buildings and transport technology, motors, white goods, and far more have occurred. Often, researchers use patents (as well as patent citations) as an indicator of technology innovation. Building upon Popp (145), a major systematic review (146) of the evidence of induced energy innovation summarizes the results of 19 papers that econometrically estimate the elasticity of patent generation with respect to energy prices. Several of the included studies show a positive and significant association between higher prices and patenting activity for energy-using technologies in oil-, transport-, electricity-, and industry-related applications. However, studies of building technologies do not find that prices induce patenting (147), except in some cases for portable technologies, for example, small appliances and white goods (148), suggesting a central problem of principal-agent and related barriers (149).

Experience or learning curves track how prices of technologies change as more units are produced or used. Weiss et al. (150) find an average, cross-technology learning rate—the cost reduction associated with a doubling of market size—of 18% (±7%) across 15 technologies (mostly building and appliance related). However, rates of 20% to 30% were found for consumer electronics and components, heat pumps, and compact fluorescent light (CFL) technologies, with high learning in CFL technologies (in particular) reinforced by several subsequent studies. Rubin et al. (151) review the learning rates reported for 11 power generation technologies, including two-factor models relating cost to cumulative expenditures for R&D. They find a substantial variability that sometimes is as large as an order of magnitude in reported learning rates across different studies and conclude that a better understanding of how different factors and assumptions affect the cost of energy technologies and their deployment is warranted.

Innovation that increases energy productivity also includes organizational and behavioral changes, which often go along with the adoption and diffusion of technological innovation. Indeed, the World Bank defines innovation largely in terms of adoption by developing countries of known but underutilized technologies. Two major reviews of the Porter hypothesis—that environmental regulation can enhance firm competitiveness—find positive evidence (152, 153), and a major factor appears to be organizational as well as technological innovation in response to regulatory pressures. Among other factors, innovation reduces resource use and business costs, at least after an adjustment period. However, the Porter hypothesis literature rarely separates energy from other factors.

Over the past decade, studies of the EU Emission Trading System (EU ETS) (154, 155) have emerged. Rogge et al. (155) report that its introduction did indeed accelerate R&D activities within regulated firms, largely focused on carbon capture and storage and energy

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

efficiency. Gulbrandsen & Stenqvist (156) find the EU ETS to have influenced firm innovation strategies, increasing focus on energy efficiency, but not sufficient to scale up or deploy radical new technologies. Most of these studies note that the EU ETS induced organizational changes in firms, giving energy use and emissions greater managerial attention. These studies focus mainly on the micro—firm-level impacts. At the national energy system level, evidence of how much of the observed improvement in national energy intensities shown in **Figure 2** can be attributed to induced innovation becomes harder to disentangle from numerous other factors, including composition and other structural changes. Steinbuks & Neuhoff (157) find that technical change is responsible for at least three-quarters of the long-run total efficiency improvement across US manufacturing sectors, through embodiment of improved technology in capital stock. Moshiri & Duah (158) decompose aggregate energy demand in Canada into a scale, composition, and technique (intrasectoral energy intensity changes) partitioning and find some evidence of price-induced innovation. Sue Wing (159) finds that up until the energy price shocks in the 1970s, innovation was energy using and almost exclusively exogenous. In contrast, over the period 1980–2000 technical change became energy saving, and toward 2000 ultimately 40% of total (disembodied) technical change can be attributed to induced technical change (see figure 7 in 159). Finally, Carraro & De Cian (160) find that the stock of (general) R&D enhances energy-saving technological change, with clear evidence for endogenous factor-specific technical change, but general R&D also increases energy-using capital investment; the net effect is that more R&D (in the absence of incentives to do otherwise) increases energy demand.

A final approach to assessing innovation at an aggregate level derives more explicitly from its implication of asymmetry. Grubb et al. (67) note that behavioral and organizational innovation brings agents closer to the existing technology frontier—what they call a first domain process—hence generating an overall Pareto improvement, while movement of the technological frontier (and infrastructure investment) generates new knowledge, options, and skills. In neither case would such developments reverse just because economic conditions change. To the extent that they are driven by energy prices (either directly or indirectly), this implies that price elasticities should be asymmetric. The most comprehensive econometric evaluation of this to date (161) analyzes 15 OECD countries over 49 years, finding statistically significant evidence for a combination of both stochastic exogenous trends and asymmetric price responses.

However, as with other dimensions of energy efficiency, understanding of innovation suffers from different definitions, metrics, and levels, namely whether innovation encompasses behavior and organization as well as technology hardware; whether it is measured in terms of physical, economic, or other indicators, and if economic, whether it includes compositional and structural improvements; and whether it is measured at the level of products, companies, sectors, or countries.

8. METHODOLOGICAL FRONTIERS IN ENERGY EFFICIENCY

In the last 40 years, numerous improvements have arisen in methodologies and tools for analyzing the effect of energy efficiency gains on energy use. Below, we outline the significant ones, with emphasis on recent developments.

8.1. Frontiers in Energy Choice Modeling

In the context of understanding consumer choices and behavior, the discrete-choice methods developed by Hausman (162) and others to understand the adoption of end use energy technologies (such as air conditioners and heating system choices) were the state of the art for some time but had the limitation of reliance on cross-sectional data, resulting in omitted variable bias and the exclusion of unobserved product attributes. The use of panel data and product fixed-effects estimators has enabled authors to overcome this limitation by eliminating unobserved costs in a study of vehicle adoption decisions (163). Other applications of methods have emerged, such as the use of agent-based models to simulate the behavior of industry agents and consumer agents (164) regarding lighting choices (165).

8.2. Frontiers in Energy Efficiency Program Evaluation

Another stream of econometric research has been in the realm of energy efficiency program evaluation. A battery of experimental and quasi-experimental techniques have been developed that help the analyst infer causal relationships from data (166). A key concern in program evaluation is the ability to identify adverse selection and inframarginal participants (or free riders). Boomhower & Davis (167) use regression discontinuity design to estimate inframarginal participation in energy efficiency subsidy schemes, while Alberini & Towe (168) combine statistical matching and panel fixed-effects estimators to compare the benefits of information provision with those of energy efficiency incentives. Although these methods are useful, another powerful tool for empirical policy evaluation is the RCT. This method has been applied extensively in evaluations of energy efficiency interventions (52, 53, 143). The approach is not without its critics, and some concerns about the external validity of results have been raised (169). One of the single most important advances in the understanding of energy efficiency outcomes of energy efficiency–related policies and programs has been combinations of the implementation of large-scale RCTs with advances in econometrics, data analysis, and statistics.

The development of RCTs, new large-scale field experiments, and new data analysis techniques has elucidated unintended consequences or surprising outcomes from energy efficiency programs. Fowlie et al. (53) find that, although weatherization programs reduce household energy consumption by 10–20%, the average rate of return on such investment is −7.8%, even when accounting for the environmental benefits of emission reduction. Importantly, both private and social rates of return are positive when calculated with the ex ante predicted savings, suggesting a need for better policy design and evaluation. Even though low-income households were the target group in their study, the authors did not find any evidence of higher internal temperatures in weatherized homes (i.e., direct rebound effects). However, a before-and-after comparison was not undertaken and the measurements conducted on a particular day, at a particular time, could be considered one estimate of direct rebound. Other measurements, such as the expansion of space heating by heating more rooms or heating rooms for longer, were not assessed to our knowledge.

Allcott et al. (170) use a large-scale field experiment that imperfectly targeted and calibrated subsidies that reduce welfare by \$0.18 per subsidy dollar spent. However, the authors estimate that if subsidies were perfectly calibrated, they could increase welfare by \$2.53 per subsidy dollar spent.

Recently, machine learning (ML) techniques have been applied to both observational and experimental data. A particular appeal of ML methods is the ability to predict counterfactuals in order to test for causality. This method, combined with existing econometric techniques, has been used to examine treatment effects of energy efficiency upgrades in schools, outperforming standard panel fixed-effects approaches (171). Additionally, ML methods are useful for estimating heterogenous treatment effects and have been applied by several researchers in this regard, specifically to high-dimensional smart metering datasets (172, 173). The quantification of heterogeneity is important for improving targeting of information, subsidies, and other types of policies in order to increase their welfare impacts (173). Yet another advancement in the econometric analysis of energy efficiency is through the application of stochastic frontier analysis. This method, based on the economic theory of production, can be applied to examine how far

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

an economic entity is from the optimum, or production frontier. Stochastic frontier analysis has been used to examine underlying energy efficiency at a range of scales in the United States, the European Union, OECD countries (174), and developing countries (175).

8.3. Frontiers in Estimating Sectoral and Economy-Wide Dynamics

The understanding of energy use, energy intensity, and energy productivity at the economy-wide level has been advanced by Bruns et al. (176), who use structural vector autoregression methods to examine the role of efficiency gains in determining economy-wide energy use. Their results generally point to very large economy-wide rebounds. Saunders (30) employs a translog production function to econometrically estimate rebounds at the sector level and finds large factor substitution elasticities and rebounds in many US sectors. Wang et al. (177) find evidence for energy for which the technology parameter (factor efficiency gain) can be econometrically estimated and thus endogenized, as it appears to rise and fall with energy cost share. Standard methods can thus be changed to incorporate this endogenization analytically.

To understand overall dynamics across sectors, demand, and supply, researchers use general equilibrium (GE) because it computes equilibrium for all markets at endogenously calculated prices. Allan et al. (178) first introduced computable general equilibrium (CGE) modeling into the exploration of the effects of energy efficiency gains on energy use. Wei (132) followed with a theoretical GE formulation he used to develop analytic conditions around the energy efficiency–energy use interaction. Turner (179) used CGE modeling to discover a disinvestment effect that leads to lower energy use. Lemoine (180) developed a generalized GE framework that allows for an indefinite number of producers and consumers and confirmed that flexibility of the economy is key to understanding how efficiency gains affect energy use—flexibility both in and among producers to substitute factor inputs and flexibility of consumers to adjust their demand profile among multiple goods and services offerings. Fullerton & Ta (181) developed a GE model that embeds a general expression for household utility and used this to explore the effects of exogenous changes on energy efficiency.

There is a deep need for further empirical analysis to create more definitive conclusions about the energy efficiency–energy use dynamic. For instance, Lemoine's (180) framework, to be practical for empirical use, requires estimation of multiple parameters, primarily the elasticities of factor substitutions and consumer substitution elasticities among products demanded and the required explicit functional forms. Pure input-output models are not suitable when they use strict Leontief-type (fixed factor) functional forms, as the functional forms for production need to allow substitution among input factors and to be tied to functional forms for consumption that allow substitution among products demanded. For a fuller picture, GE methodologies must further incorporate time dynamics of the type found in neoclassical growth models, as in the manner of Rausch & Schwerin (182).

9. CONCLUSIONS

Deploying energy efficiency is necessary and is one of the key strategies needed to achieve climate change mitigation, to reduce pollution and its impacts on health and the environment, and to provide affordable energy services. Over the last 40 years, researchers have developed a better understanding of the role of energy efficiency, from the individual user to economy-wide levels. Researchers studied end use energy technology improvements, energy efficiency programs and policy outcomes, and the dynamics and equilibriums that form as energy productivity improves. Although all these aspects may be nested under the umbrella of energy efficiency research, they are in fact examining different but often intertwined effects. Indeed, across fields and research

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

topics, many researchers use energy efficiency according to different definitions, as called for per problem context, with the common goal of characterizing the value created using less energy, but this can be misleading if applied in inappropriate contexts.

Innovation in energy-saving technologies (such as lighting) has lowered energy service costs and induced technology adoption. However, whereas it is trivial to define efficiency metrics at the device level, assessments increase in complexity as scale increases. For example, at the level of a region or country, energy intensity (such as energy use per unit of GDP), albeit a crude metric, is frequently used as a proxy for energy efficiency. We find that technological energy efficiency improvements generally increase economic welfare. But this may have negative externalities (such as rebound effects that increase emissions leading to climate change and health damage from ground-level air pollution), thus making it difficult in the absence of appropriate policy necessarily leading to increased social welfare. In the case of policy interventions to mitigate market barriers or failures from energy–economy systems, poorly designed policy mechanisms could also lead to a reduction in economic welfare. The overall welfare effects are difficult to measure, as they depend on price and substitution elasticities resulting from energy efficiency improvements, which will lead to new equilibrium prices and quantities. Continuous ex post assessments are critical to support policy making and provide learning opportunities to stakeholders.

Overall, future research would benefit from bringing together researchers from different fields to shed new light on energy efficiency questions. Examples of such endeavors include (*a*) at the microlevel, a better understanding of consumer choice and behavior by combining insights from engineering and the advanced metering and sensing infrastructure with insights from microeconomic theory and the theory of choice and with behavioral economists' models; (*b*) at the program evaluation level, continuing development of methods to understand causal inferences using econometrics and ML methods to better understand program outcomes; and (*c*) at the macrolevel, the development of flexible and credible GE models that capture environmental and climate externalities outcomes and that have good input data to enable us to understand the dynamics of energy efficiency improvements across the economy, the environment, and society.

SUMMARY POINTS

1. Over the last four decades different disciplinary approaches independently adopted different definitions of energy efficiency to answer specific problems. Different definitions, if inappropriately applied, can lead to erroneous interpretations of outcomes of interest. Definitions become less clear with increasing system scale and complexity.
2. Energy consumption per unit of gross domestic product (energy intensity) across countries showed significant reductions over the last century, with their magnitude varying by the stage of economic development and showing limited convergence of per-capita energy consumption.
3. Estimates of the energy efficiency gap (i.e., the difference in energy consumption between what is currently observed and what energy consumption would be if the most efficient technologies were adopted), though imperfect, have proved extremely useful as a guide to R&D and to policy design.
4. Overall, there is strong support in the literature to conclude that market barriers, market failures, behavioral failures, policy distortions, negative externalities, and issues of

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

culture and norms justify policy intervention and innovation policies to improve energy efficiency.

5. Energy efficiency improvements generally increase economic welfare. Well-designed policy interventions, and energy efficiency itself, appear to be consistently economic welfare–increasing, externalities aside.
6. Innovation in energy-saving technologies is an important driver in improving aggregate energy efficiency deployment by lowering costs of technologies and inducing their adoption. The productivity of numerous energy-using products has improved dramatically.
7. There is still uncertainty and difficulty in measuring rebound effects, which may limit the ability of energy efficiency improvements to reduce or constrain overall energy use. There is some evidence that economy-wide rebound magnitudes are large.
8. Rebound-suppressing policies can disproportionately harm consumers experiencing energy poverty.
9. Understanding the overall outcomes associated with energy-efficient strategies and policies requires cross-disciplinary and interdisciplinary efforts that necessitate engineering, economics, and social science collaboration.
10. There are trade-offs between economic welfare and the social welfare implications of emissions reductions from reduced energy use. These trade-offs vary across countries, given the varying levels of their economic development.
11. Methodological advances for examining energy efficiency effects on energy use have been substantial. Primary advances include randomized control trials (RCTs) coupled with appropriate econometric methods, development in econometric methods and laboratory/field experiments, agent-based modeling, general equilibrium methods, and behavioral science. No methodological approach has so far been unfruitful.

FUTURE ISSUES

1. There is a need for more analyses of energy efficiency and its impact at various stages of development and in the context of complex systems for which, due to systems interactions, the outcome will not be the simplistic aggregate result of energy savings from individual efficient technologies. We need analyses that value energy efficiency at social prices, and we also need a deeper understanding of the key relationships among social efficiency, technological efficiency, induced innovation, rebound, and distributional consequences between rich and poor in both the short and longer terms.
2. There is a need to further build the evidence base delineating outcomes from energy efficiency technologies, strategies, and policies. Synthesis of RCTs and other empirical work in systematic reviews, case studies, and meta-analyses is warranted, particularly in developing countries.
3. Findings from energy efficiency estimates need to be presented with an explicit description of domain, boundaries, and context (e.g., micro versus macro domain, level of economic development, demographics, income distribution, likely growth in demand).

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

4. There is strong evidence that market failures and policy distortions lead to deviations between the theoretical and the practical potential of energy efficiency improvements, but their magnitude needs to be quantified. Uncertainties are higher when unexplained behavioral characteristics are considered. These estimates are critical to better inform policies, making policy research as important as efficiency research itself.
5. Much more work needs to be undertaken to quantify indirect impacts or cobenefits of energy efficiency, particularly in terms of avoided or induced externalities from, for example, air pollution, climate change, congestion, and waste.
6. There is a need for more sophisticated functional forms to properly address energy efficiency–energy use interactions that consider more holistic upstream and downstream energy efficiency concepts.
7. Further, robust methodologies must account for energy efficiency–energy use time dynamics, building on the time-honored methods pioneered by neoclassical growth economists.
8. Policy evaluation (ex post) is critical to ascertaining the welfare effects of energy efficiency policies (namely in the presence of rebound effects and different policy mixes).
9. Modeling is only as good as the underlying data. Researchers should continue to make their datasets available to the community and, to the extent possible, to include granular data that follow key quantities of interest over time. Such new streams of data, though important, may still not be able to solve questions of causality.
10. Methodology improvements and richer datasets will matter to the formulation of sound energy efficiency policies and will foment greater confidence in deploying them.
11. As countries make pledges and adopt goals aimed toward carbon neutrality, it will become even more relevant to understand energy efficiency's contribution to such goals across different countries and over time.
12. So far, the literature has paid little attention to the implications of pricing energy at its societal cost (i.e., including environmental, health, and climate change externalities), which in turn has implications for optimal investments of energy efficiency and their distributional consequences.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

H.D.S., J.R., and I.M.L.A. coordinated this collaboration and made specific contributions to the text throughout. They adjusted the article structure at various draft stages and shepherded Section 9, the Summary Points, and the Future Issues. I.M.L.A. created **Figure 1**. R.F. provided the bulk of Section 3, including the creation of **Figure 2**. M.G. contributed to Sections 5–7. R.L. co-coordinated Section 4 and contributed to Section 6. R.M. contributed to Section 6 and to other sections as well. D.M.M. made significant contributions to Section 6. L.M. was primarily responsible for Section 5. S.S. was primarily responsible for Section 2. He also made a significant contribution to Section 4. D.S. made significant contributions to Sections 2 and 8. All other authors made significant contributions to the text and explanatory formulations in various parts of the article.

ACKNOWLEDGMENTS

The authors would like to thank three anonymous reviewers for extremely useful and incisive comments. We also apologize to several dozen researchers whose contributions could not be included owing to page limitations. R.F. and D.M.M. acknowledge support from the Grantham Research Institute on Climate Change and the Environment at the London School of Economics and from the ESRC Centre for Climate Change Economics and Policy (CCCEP) (ref. ES/R009708/1). M.G., R.L., T.O., and S.S. acknowledge funding from UKRI/EPSRC under the Heat, Buildings, Digital and Flexibility Themes of the Centre for Energy Demand Solutions (CREDS) (ref. EP/R 035288/1).

LITERATURE CITED

1. Rubin ES, Cooper RN, Frosch RA, Lee TH, Marland G, et al. 1992. Realistic mitigation options for global warming. *Science* 257(5067):148–266
2. NRC (Natl. Res. Counc.) 2010. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. Washington, DC: The National Academies Press. **https://doi.org/10.17226/12794**
3. Azevedo IML. 2014. Consumer end-use energy efficiency and rebound effects. *Annu. Rev. Environ. Resour.* 39:393–418
4. Srinivasan S, Mosdale R, Stevens P, Yang C. 1999. Fuel cells: reaching the era of clean and efficient power generation in the twenty-first century. *Annu. Rev. Energy Environ.* 24:281–328
5. Koomey JG, Matthews HS, Williams E. 2013. Smart everything: Will intelligent systems reduce resource use? *Annu. Rev. Environ. Resour.* 38:311–43
6. Kononov Y. 1990. Impact of economic restructuring of energy efficiency in the USSR. *Annu. Rev. Energy* 15:505–12
7. Friedmann R, Sheinbaum C. 1998. Mexican electric end-use efficiency: experiences to date. *Annu. Rev. Energy Environ.* 23:225–52
8. Schipper L, Howarth R, Geller H. 1990. United States energy use from 1973 to 1987: the impacts of improved efficiency. *Annu. Rev. Energy* 15:455–504
9. Nadel S. 2002. Appliance and equipment efficiency standards. *Annu. Rev. Energy Environ.* 27:159–92
10. Berndt ER. 1978. Aggregate energy, efficiency, and productivity measurement. *Annu. Rev. Energy* 3:225–73
11. Rosenfeld A. 1999. The art of energy efficiency: protecting the environment with better technology. *Annu. Rev. Energy Environ.* 24:33–82
12. Jaskow P. 1995. Utility-subsidized energy-efficiency programs. *Annu. Rev. Energy Environ.* 20:526–34
13. Patterson MG. 1996. What is energy efficiency? Concepts, indicators and methodological issues. *Energy Policy* 24(5):377–90
14. Cleveland CJ, Kaufmann RK, Stern DI. 2000. Aggregation and the role of energy in the economy. *Ecol. Econ.* 32(2):301–17
15. Pérez-Lombard L, Ortiz J, Velázquez D. 2013. Revisiting energy efficiency fundamentals. *Energy Effic.* 6(2):239–54
16. Ball WH. 1961. Thermal insulation in dwellings. *Can. Build. Dig.* 1961–04. **https://doi.org/10.4224/40000774**
17. Carlsson B, Elmroth A, Engvall PA. 1980. *Airtightness and thermal insulation: building design solutions*. Stockholm: Swedish Counc. Build. Res. D37:1980. **https://www.aivc.org/resource/airtightness-and-thermal-insulation-building-design-solutions**
18. Chan NW, Gillingham K. 2015. The microeconomic theory of the rebound effect and its welfare implications. *J. Assoc. Environ. Resour. Econ.* 2(1):133–59

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

19. Meier AK. 1982. *Supply curves of conserved energy*. PhD Thesis, Univ. Calif., Berkeley
20. Blumstein C, Stoft SE. 1995. Technical efficiency, production functions and conservation supply curves. *Energy Policy* 23(9):765–68
21. Rosenfeld A, Atkinson C, Koomey J, Meier A, Mowris RJ, Price L. 1993. Conserved energy supply curves for U.S. buildings. *Contemp. Econ. Policy* 11(1):45–68
22. McKinsey & Co. 2007. *Reducing the U.S. Greenhouse Gas Emissions: How Much at What Cost? U.S. Greenhouse Gas Abatement Mapping Initiative*. *Executive Report*. Chicago: McKinsey & Co.
23. Jaffe AB, Stavins RN. 1994. The energy-efficiency gap: What does it mean? *Energy Policy* 22(10):804–10
24. Rosenow J, Bayer E. 2017. Costs and benefits of energy efficiency obligations: a review of European programmes. *Energy Policy* 107:53–62
25. Tirole J. 2008. Some economics of global warming. *Riv. Polit. Econ.* 98(6):9–42
26. Stern DI. 2012. Modeling international trends in energy efficiency. *Energy Econ*. 34(6):2200–8
27. Ang BW. 2004. Decomposition analysis for policymaking in energy: Which is the preferred method? *Energy Policy* 32(9):1131–39
28. Ang BW. 2006. Monitoring changes in economy-wide energy efficiency: from energy-GDP ratio to composite efficiency index. *Energy Policy* 34(5):574–82
29. Goh T, Ang BW. 2019. Tracking economy-wide energy efficiency using LMDI: approach and practices. *Energy Effic*. 12(4):829–47
30. Saunders H. 2013. Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. *Technol. Forecast. Soc. Change* 80(7):1317–30
31. Belzer DB. 2014. *A comprehensive system of energy intensity indicators for the U.S.: methods, data and key trends*. Tech. Rep. 22267. Pac. Northwest Natl. Lab., Richland, WA. **https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22267.pdf**
32. IEA (Int. Energy Agency). 2019. *Market report series: energy efficiency 2019*. Rep., IEA, Paris. **https://webstore.iea.org/market-report-series-energy-efficiency-2019**
33. Fouquet R, Pearson PJG. 1998. A thousand years of energy use in the United Kingdom. *Energy J.* 19(4):1–41
34. Bolt J, van Zanden JL. 2014. The Maddison Project: collaborative research on historical national accounts. *Econ. Hist. Rev.* 67(3):627–51
35. Csereklyei Z, Rubio-Varas MM, Stern DI. 2016. Energy and economic growth: the stylized facts. *Energy J.* 37(2):223–55
36. BP (Br. Pet.). 2019. *BP Statistical Review of World Energy 2019*. London: BP. **https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf**
37. Carter SB, Gartner SS, Haines MR, Olmstead AL, Sutch R, Wright G. 2001. *Historical Statistics of the United States 2001*. Cambridge, MA: Cambridge Univ. Press. **https://hsus.cambridge.org/HSUSWeb/toc/hsusHome.do**
38. Fouquet R. 2008. *Heat, Power and Light Revolutions in Energy Services*. Cheltenham, UK: Edward Elgar Publ.
39. Kander P, Malanima A, Warde P. 2013. *Power to the People: Energy in Europe Over the Last Five Centuries*. Princeton, NJ: Princeton Univ. Press
40. Fouquet R, Pearson PJG. 2012. The long run demand for lighting: elasticities and rebound effects in different phases of economic development. *Econ. Energy Environ. Policy* 1(1):83–110
41. Mundaca L, Markandya A, Nørgaard J. 2013. Walking away from a low-carbon economy? Recent and historical trends using a regional decomposition analysis. *Energy Policy* 61:1471–80
42. Marcotullio PJ, Schulz NB. 2007. Comparison of energy transitions in the United States and developing and industrializing economies. *World Dev*. 35(10):1650–83
43. Ezcurra R. 2007. Distribution dynamics of energy intensities: a cross-country analysis. *Energy Policy* 35(10):5254–59
44. Mulder P, de Groot HLF. 2012. Structural change and convergence of energy intensity across OECD countries, 1970–2005. *Energy Econ*. 34(6):1910–21
45. van Benthem A. 2015. Energy leapfrogging. *J. Assoc. Environ. Resour. Econ*. 2(1):93–132

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

46. Hart R. 2018. Rebound, directed technological change, and aggregate demand for energy. *J. Environ. Econ. Manag.* 89:218–34
47. Sutherland R. 1991. Market barriers to energy-efficiency investments. *Energy J.* 12(3):15–34
48. Golove WH, Eto JH. 1996. *Market barriers to energy efficiency: a critical reappraisal of the rationale for public policies to promote energy efficiency*. Rep. LBL-38059. Lawrence Berkeley National Lab., Berkeley, CA. **https://eta-publications.lbl.gov/sites/default/files/lbnl-38059.pdf**
49. Lovins AB. 2005. Taxonomy for breaking through the economic limits of energy efficiency. *Energy Effic. Taxon. Overview Encycl. Energy* 2:383–401
50. Sanstad AH, Howarth RB. 1994. 'Normal' markets, market imperfections and energy efficiency. *Energy Policy* 22(10):811–18
51. Sorrell S, O'Malley E, Schleich J, Scott S. 2004. *The Economics of Energy Efficiency: Barriers to Cost-Effective Investment*. Cheltenham, UK: Edward Elgar Publ.
52. Allcott H, Greenstone M. 2017. *Measuring the welfare effects of residential energy efficiency programs*. NBER Work. Pap. 23386
53. Fowlie M, Greenstone M, Wolfram C. 2018. Do energy efficiency investments deliver? Evidence from the weatherization assistance program. *Q. J. Econ.* 133(3):1597–644
54. Gillingham K, Keyes A, Palmer K. 2018. Advances in evaluating energy efficiency policies and programs. *Annu. Rev. Resour. Econ.* 10:511–32
55. Fouquet R. 2018. Consumer surplus from energy transitions. *Energy J.* 39(3):167–88
56. Allcott H, Greenstone M. 2012. Is there an energy efficiency gap? *J. Econ. Perspect.* 26(1):3–28
57. Kahneman D, Thaler RH. 2006. Anomalies: utility maximization and experienced utility. *J. Econ. Perspect.* 20(1):221–34
58. Wilson C, Dowlatabadi H. 2007. Models of decision making and residential energy use. *Annu. Rev. Environ. Resour.* 32:169–203
59. Gillingham K, Newell R, Palmer K. 2006. Energy efficiency policies: a retrospective examination. *Annu. Rev. Environ. Resour.* 31:161–92
60. Nadel S. 2003. *Appliance & equipment efficiency standards in the US: accomplishments, next steps and lessons learned*. Paper presented at eceee Summer Study on Energy Efficiency. **https://www.eceee.org/static/media/uploads/site-2/library/conference_proceedings/eceee_Summer_Studies/2003c/Panel_1/1045nadel/paper.pdf**
61. Ürge-Vorsatz D, Novikova A, Köppel S, Boza-Kiss B. 2009. Bottom-up assessment of potentials and costs of CO_2 emission mitigation in the buildings sector: insights into the missing elements. *Energy Effic.* 2(4):293–316
62. Lin J. 2002. Appliance efficiency standards and labeling programs in China. *Annu. Rev. Energy Environ.* 27:349–67
63. Roy J, Chakravarty D, Dasgupta S, Chakraborty D, Pal S, Ghosh D. 2018. Where is the hope? Blending modern urban lifestyle with cultural practices in India. *Curr. Opin. Environ. Sustain.* 31(February):96–103
64. Cao X, Dai X, Liu J. 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build.* 128:198–213
65. Greening L, Sanstad A, McMahon J, Wenzel T, Pickle S. 1996. Retrospective analysis of national energy efficiency standards for refrigerators. In *Proceedings of the ACEEE Summer Study of Energy Efficiency in Buildings*, 9.101–9.109. Washington, DC: American Council for an Energy-Efficient Economy. **https://www.aceee.org/files/proceedings/1996/data/papers/SS96_Panel9_Paper11.pdf**
66. Dale L, Antinori C, McNeil M, McMahon J, Berkeley L. 2002. Retrospective evaluation of declining price for energy efficient appliances. In *Proceedings of the ACEEE Summer Study of Energy Efficiency in Buildings*, 9.55–9.70 Washington, DC: American Council for an Energy-Efficient Economy. **https://www.aceee.org/files/proceedings/2002/data/papers/SS02_Panel9_Paper05.pdf**
67. Grubb M, Hourcade JC, Neuhoff K. 2014. *Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development*. Abingdon, UK: Routledge
68. Knittel CR. 2011. Automobiles on steroids: product attribute trade-offs and technological progress in the automobile sector. *Am. Econ. Rev.* 101(7):3368–99
69. Barbieri N. 2015. Investigating the impacts of technological position and European environmental regulation on green automotive patent activity. *Ecol. Econ.* 117:140–52

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

70. Newell RG, Jaffe AB, Stavins RN. 1999. The induced innovation hypothesis and energy-saving technological change. *Q. J. Econ.* 3(August):941–75
71. Wei M, Smith SJ, Sohn MD. 2017. Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US. *Appl. Energy* 191:346–57
72. Mundaca L, Sonnenschein J, Steg L, Höhne N, Ürge-Vorsatz D. 2019. The global expansion of climate mitigation policy interventions, the Talanoa Dialogue and the role of behavioural insights. *Environ. Res. Commun.* 1(6):061001
73. Gillingham K, Newell RG, Palmer K. 2009. Energy efficiency economics and policy. *Annu. Rev. Resour. Econ.* 1:597–620
74. Gellings CW, Wikler G, Ghosh D. 2006. Assessment of U.S. electric end-use efficiency potential. *Electr. J.* 19(9):55–69
75. Ito K. 2015. Asymmetric incentives in subsidies: evidence from a large-scale electricity rebate program. *Am. Econ. J. Econ. Policy* 7(3):209–237
76. Labandeira X, Labeaga JM, Linares P, López-Otero X. 2020. The impacts of energy efficiency policies: meta-analysis. *Energy Policy* 147:111790
77. Krishnamurti T, Schwartz D, Davis A, Fischhoff B, Bruine de Bruin W, et al. 2012. Preparing for smart grid technologies: a behavioral decision research approach to understanding consumer expectations about smart meters. *Energy Policy* 41:790–97
78. Bittle R, Valesano R, Thaler G. 1979. The effects of daily feedback on residential electricity usage as a function of usage level and type of feedback information. *J. Environ. Syst.* 9:275–87
79. Hutton RB, Mauser GA, Filiatrault P, Ahtola OT. 1986. Effects of cost-related feedback on consumer knowledge and consumption behavior: a field experimental approach. *J. Consum. Res.* 13(3):327–36
80. Bager S, Mundaca L. 2017. Making 'Smart Meters' smarter? Insights from a behavioural economics pilot field experiment in Copenhagen, Denmark. *Energy Res. Soc. Sci.* 28(April):68–76
81. Lesic V, Glasgo B, Krishnamurti T, Bruine de Bruin W, Davis M, Azevedo IL. 2019. Comparing consumer perceptions of appliances' electricity use to appliances' actual direct-metered consumption. *Environ. Res. Commun.* 1(11):111002
82. Nadel S, Goldstein D. 1996. Appliance and equipment efficiency standards: history, impacts, current status, and future directions. In *Proceedings of the ACEEE Summer Study of Energy Efficiency in Buildings*, pp. 1–20. Washington, DC: Am. Counc. Energy-Efficient Econ. **https://www.aceee.org/sites/default/files/publications/researchreports/A963.pdf**
83. Buchanan K, Russo R, Anderson B. 2015. The question of energy reduction: the problem(s) with feedback. *Energy Policy* 77:89–96
84. Allcott H. 2011. Social norms and energy conservation. *J. Public Econ.* 95(9–10):1082–95
85. Andor MA, Fels KM. 2018. Behavioral economics and energy conservation—a systematic review of non-price interventions and their causal effects. *Ecol. Econ.* 148(July 2017):178–210
86. Schultz PW, Nolan JM, Cialdini RB, Goldstein NJ, Griskevicius V. 2018. The constructive, destructive, and reconstructive power of social norms: reprise. *Perspect. Psychol. Sci.* 13(2):249–54
87. Tiefenbeck V, Staake T, Roth K, Sachs O. 2013. For better or for worse? Empirical evidence of moral licensing in a behavioral energy conservation campaign. *Energy Policy* 57:160–71
88. Abrahamse W, Steg L, Vlek C, Rothengatter T. 2005. A review of intervention studies aimed at household energy conservation. *J. Environ. Psychol.* 25(3):273–91
89. Allcott H, Mullainathan S. 2010. Behavior and energy policy. *Policy Forum* 327(March):1204–6
90. Harding M, Hsiaw A. 2014. Goal setting and energy conservation. *J. Econ. Behav. Organ.* 107:209–27
91. Katzev RD, Johnson TR. 1984. Comparing the effects of monetary incentives and foot-in-the-door strategies in promoting residential electricity conservation. *J. Appl. Soc. Psychol.* 14(1):12–27
92. McClelland L, Cook SW. 1980. Promoting energy conservation in master-metered apartments through group financial incentives. *J. Appl. Soc. Psychol.* 10(1):20–31
93. Winett RA, Kagel JH, Battalio RC, Winkler RC. 1978. Effects of monetary rebates, feedback, and information on residential electricity conservation. *J. Appl. Psychol.* 63(1):73–80
94. Slavin RE, Wodarski JS, Blackburn BL. 1981. A group contingency for electricity conservation in master-metered apartments. *J. Appl. Behav. Anal.* 14(3):357–63

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

95. Dolan P, Metcalfe RD. 2015. *Neighbors, knowledge, and nuggets: two natural field experiments on the role of incentives on energy conservation*. Work. Pap., Becker Friedman Inst. Econ., Univ. Chicago. **https://doi.org/10.2139/ssrn.2589269**
96. Nadel S. 1992. Utility demand-side management experience and potential—a critical review. *Annu. Rev. Energy Environ.* 17:507–35
97. Delmas MA, Fischlein M, Asensio OI. 2013. Information strategies and energy conservation behavior: a meta-analysis of experimental studies from 1975 to 2012. *Energy Policy* 61:729–39
98. Boza-Kiss B, Moles-Grueso S, Urge-Vorsatz D. 2013. Evaluating policy instruments to foster energy efficiency for the sustainable transformation of buildings. *Curr. Opin. Environ. Sustain.* 5(2):163–76
99. Cornelis E. 2019. History and prospect of voluntary agreements on industrial energy efficiency in Europe. *Energy Policy* 132(May):567–82
100. Ekins P, Etheridge B. 2006. The environmental and economic impacts of the UK climate change agreements. *Energy Policy* 34(15):2071–86
101. UK Environment Agency. 2015. *CRC energy efficiency scheme: allowances*. Rep., UK Environment Agency, Bristol, UK. **https://www.gov.uk/crc-energy-efficiency-scheme-allowances**
102. Bento A, Gillingham K, Jacobsen MR, Knittel CR, Leard B, et al. 2018. Flawed analysis of U.S. auto fuel economy standard. *Science* 362(6419):1119–21
103. Billingsley MA, Hoffman IM, Stuart E, Schiller SR, Goldman CA, LaCommare K. 2014. *The program administrator cost of saved energy for utility customer-funded energy efficiency programs*. Rep., US Dep. Energy, Washington, DC. **https://www.osti.gov/servlets/purl/1129528/**
104. Madlener R, Hauertmann M. 2012. *Rebound effects in German residential heating: Do ownership and income matter?* FCN Work. Pap. 2/2011. **https://doi.org/10.2139/ssrn.1887030**
105. Aydin E, Kok N, Brounen D. 2017. Energy efficiency and household behavior: the rebound effect in the residential sector. *RAND J. Econ.* 48(3):749–82
106. McCoy D, Kotsch RA. 2021. Quantifying the distributional impact of energy efficiency measures. *Energy J.* 42(6). **https://doi.org/10.5547/01956574.42.6.dmcc**
107. Ryan L, Campbell N. 2012. *Spreading the net: the multiple benefits of energy efficiency improvements*. Rep., Int. Energy Agency, Paris. **https://www.ourenergypolicy.org/wp-content/uploads/2014/04/Spreading_the_Net.pdf**
108. IPCC (Intergov. Panel Clim. Change). 2018. Mitigation pathways compatible with 1.5°C in the context of sustainable development. In *Special Report: Global Warming of 1.5°C*, ed. V Masson-Delmotte, P Zhai, H-O Pörtner, D Roberts, J Skea, et al. Geneva: World Meteorol. Organ. 32 pp. **https://www.ipcc.ch/sr15/chapter/chapter-2/**
109. de la Rue du Can S, Pudleiner D, Pielli K. 2018. Energy efficiency as a means to expand energy access: a Uganda roadmap. *Energy Policy* 120(January):354–64
110. Thomas BA, Azevedo IL. 2013. Estimating direct and indirect rebound effects for US households with input-output analysis. Part 1: Theoretical framework. *Ecol. Econ.* 86:199–210
111. Thomas BA, Azevedo IL. 2014. Should policy-makers allocate funding to vehicle electrification or end-use energy efficiency as a strategy for climate change mitigation and energy reductions? Rethinking electric utilities efficiency programs. *Energy Policy* 67:28–36
112. Khazzoom JD. 1980. Economic implications of mandated efficiency standard for household appliances. *Energy J.* 1(4):21–40
113. Jevons WS. 1865. *The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines*. New York: Macmillan
114. Brookes L. 1979. A low energy strategy for the UK by G. Leach et al: a review and reply. *Atom* 269:3–8
115. Grubb M. 1990. Energy efficiency and economic fallacies. *Energy Policy* 18(4):483–85
116. Saunders H. 1992. The Khazzoom-Brookes postulate and neoclassical growth. *Energy J.* 13(4):131–38
117. Pearson P, Fouquet R. 1996. Energy efficiency, economic efficiency and future carbon dioxide emissions from the developing world. *Energy J.* 17(4):1–26
118. Roy J. 2000. The rebound effect: some empirical evidence from India. *Energy Policy* 28(6–7):433–38
119. Lowe R. 2003. A theoretical analysis of price elasticity of energy demand in multi-stage energy conversion systems. *Energy Policy* 31:1699–704

120. Schipper L, ed. 2000. *Energy Policy* 28(6–7)
121. Gillingham K, Rapson D, Wagner G. 2016. The rebound effect and energy efficiency policy. *Rev. Environ. Econ. Policy* 10(1):68–88
122. Saunders H. 2008. Fuel conserving (and using) production functions. *Energy Econ.* 30(5):2184–235
123. Saunders H. 2013. Recent evidence for large rebound: elucidating the drivers and their implications for climate change models. *Energy J.* 31(1):23–48
124. Sorrell S. 2007. *The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. Rep., UK Energy Research Centre, London
125. Sorrell S. 2014. Energy substitution, technical change and rebound effects. *Energies* 7(5):2850–73
126. Stern DI. 2020. How large is the economy-wide rebound effect? *Energy Policy* 147(August):111870
127. Santarius T, Walnum HJ, Aall C, eds. 2016. *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*. Cham, Switz.: Springer Int. Publ.
128. Schmitz H, Madlener R. 2020. Direct and indirect energy rebound effects in German households: a linearized almost ideal demand system approach. *Energy J.* 41(5):89–118
129. Chakravarty D, Dasgupta S, Roy J. 2013. Rebound effect: how much to worry? *Curr. Opin. Environ. Sustain.* 5(2):216–28
130. Chakravarty D, Roy J. 2016. The Global South: new estimates and insights from urban India. In *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*, ed. T Santarius, HJ Walnum, C Aall, pp. 55–72. Cham, Switz.: Springer Int. Publ.
131. Druckman A, Chitnis M, Sorrell S, Jackson T. 2011. Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy* 39(6):3572
132. Wei T. 2010. A general equilibrium view of global rebound effects. *Energy Econ.* 32(3):661–72
133. Wei T, Liu Y. 2017. Estimation of global rebound effect caused by energy efficiency improvement. *Energy Econ.* 66:27–34
134. Stern D, Kander A. 2012. The role of energy in the Industrial Revolution and modern economic growth. *Energy* 33(3):125–52
135. Liu Y, Wei T, Park D. 2019. Macroeconomic impacts of energy productivity: a general equilibrium perspective. *Energy Effic.* 12(7):1857–72
136. Stern DI. 2017. How accurate are energy intensity projections? *Clim. Change* 143(3–4):537–45
137. Brockway PE, Sorrell S, Semieniuk G, Heun MK, Court V. 2021. Energy efficiency and economy-wide rebound effects: a review of the evidence and its implications. *Renew. Sustain. Energy Rev.* 141:110781
138. Wei T, Zhou J, Zhang H. 2019. Rebound effect of energy intensity reduction on energy consumption. *Resour. Conserv. Recycl.* 144(February):233–39
139. Lamb WF, Wiedmann T, Pongratz J, Andrew R, Crippa M, et al. 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **https://doi.org/10.1088/1748-9326/abee4e**
140. UNEP (UN Environ. Prog.) 2016. *The emissions gap report 2016*. Rep., UNEP, Nairobi. **https://www.unep.org/resources/emissions-gap-report-2016**
141. Maamoun N. 2019. The Kyoto Protocol: empirical evidence of a hidden success. *J. Environ. Econ. Manag.* 95:227–56
142. Saunders H. 2013. Is what we think of as 'rebound' really just income effects in disguise? *Energy Policy* 57:308–17
143. Smil V. 2003. *Energy at the Crossroads: Global Perspectives and Uncertainties*. Cambridge, MA: MIT Press
144. Lichtenberg FR. 1986. Energy prices and induced innovation. *Res. Policy* 15(2):67–75
145. Popp D. 2019. *Environmental policy and innovation: a decade of research*. NBER Work. Pap. 2563
146. Grubb M, Drummond P, Poncia A, McDowall W, Popp D, et al. 2021. Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO_2 mitigation. *Environ. Res. Lett.* 16:043007
147. Costantini V, Crespi F, Palma A. 2017. Characterizing the policy mix and its impact on eco-innovation: a patent analysis of energy-efficient technologies. *Res. Policy* 46(4):799–819
148. Noailly J. 2012. Improving the energy efficiency of buildings: the impact of environmental policy on technological innovation. *Energy Econ.* 34(3):795–806

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

149. Kruse J, Wetzel H. 2016. Energy prices, technological knowledge, and innovation in green energy technologies: a dynamic panel analysis of European patent data. *CESifo Econ. Stud.* 62(3):397–425
150. Weiss M, Junginger M, Patel MK, Blok K. 2010. A review of experience curve analyses for energy demand technologies. *Technol. Forecast. Soc. Change* 77(3):411–28
151. Rubin ES, Azevedo IML, Jaramillo P, Yeh S. 2015. A review of learning rates for electricity supply technologies. *Energy Policy* 86:198–218
152. Ambec S, Cohen MA, Elgie S, Lanoie P. 2013. The Porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness? *Rev. Environ. Econ. Policy* 7(1):2–22
153. Cohen MA, Tubb A. 2018. The impact of environmental regulation on firm and country competitiveness: a meta-analysis of the Porter hypothesis. *J. Assoc. Environ. Resour. Econ.* 5(2):371–99
154. Borghesi S, Cainelli G, Mazzanti M. 2015. Linking emission trading to environmental innovation: evidence from the Italian manufacturing industry. *Res. Policy* 44(3):669–83
155. Rogge KS, Schneider M, Hoffmann VH. 2011. The innovation impact of the EU emission trading system—findings of company case studies in the German power sector. *Ecol. Econ.* 70(3):513–23
156. Gulbrandsen LH, Stenqvist C. 2013. The limited effect of EU emissions trading on corporate climate strategies: comparison of a Swedish and a Norwegian pulp and paper company. *Energy Policy* 56:516–25
157. Steinbuks J, Neuhoff K. 2014. Assessing energy price induced improvements in efficiency of capital in OECD manufacturing industries. *J. Environ. Econ. Manag.* 68(2):340–56
158. Moshiri S, Duah N. 2016. Changes in energy intensity in Canada. *Energy J.* 37(4):315–42
159. Sue Wing I. 2008. Explaining the declining energy intensity of the U.S. economy. *Resour. Energy Econ.* 30(1):21–49
160. Carraro C, De Cian E. 2012. Factor-augmenting technical change: an empirical assessment. *Environ. Model. Assess.* 18(1):13–26
161. Adeyemi OI, Hunt LC. 2014. Accounting for asymmetric price responses and underlying energy demand trends in OECD industrial energy demand. *Energy Econ.* 45:435–44
162. Hausman J. 1979. Individual discount rates and the purchase and utilization of energy-using durables. *Bell J. Econ.* 10(1):33–54
163. Allcott H, Wozny N. 2014. Gasoline prices, fuel economy, and the energy paradox. *Rev. Econ. Stat.* 96(5):779–95
164. Safarzynska K. 2012. Modeling the rebound effect in two manufacturing industries. *Technol. Forecast. Soc. Change* 79(6):1135–54
165. Hicks AL, Theis TL. 2014. An agent based approach to the potential for rebound resulting from evolution of residential lighting technologies. *Int. J. Life Cycle Assess.* 19(2):370–76
166. Athey S, Imbens GW. 2017. The state of applied econometrics: causality and policy evaluation. *J. Econ. Perspect.* 31(2):3–32
167. Boomhower J, Davis LW. 2014. A credible approach for measuring inframarginal participation in energy efficiency programs. *J. Public Econ.* 113:67–79
168. Alberini A, Towe C. 2015. Information v. energy efficiency incentives: evidence from residential electricity consumption in Maryland. *Energy Econ.* 52:S30–40
169. Allcott H. 2015. Site selection bias in program evaluation. *Q. J. Econ.* 130(3):1117–65
170. Allcott H, Knittel C, Taubinsky D. 2015. Tagging and targeting of energy efficiency subsidies. *Am. Econ. Rev.* 105(5):187–91
171. Burlig F, Knittel C, Rapson D, Reguant M, Wolfram C. 2017. *Machine learning from schools about energy efficiency*. NBER Work. Pap. 23908
172. Knittel CR, Stolper S. 2019. *Using machine learning to target treatment: the case of household energy use*. NBER Work. Pap. 26531
173. Souza M. 2019. *Predictive counterfactuals for treatment effect heterogeneity in event studies with staggered adoption*. Work. Pap., Univ. Carlos III Madrid, Spain. **http://dx.doi.org/10.2139/ssrn.3484635**
174. Filippini M, Hunt LC. 2011. Energy demand and energy efficiency in the OECD countries: a stochastic demand frontier approach. *Energy J.* 32(2). **https://doi.org/10.5547/ISSN0195-6574-EJ-Vol32-No2-3**
175. Adom PK, Amakye K, Abrokwa KK, Quaidoo C. 2018. Estimate of transient and persistent energy efficiency in Africa: a stochastic frontier approach. *Energy Convers. Manag.* 166:556–68

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

176. Bruns SB, Moneta A, Stern DI. 2019. *Estimating the economy-wide rebound effect using empirically identified structural vector autoregressions*. LME Work. Pap. Ser. 2284-0400

177. Wang R, Saunders H, Moreno-Cruz J, Caldeira K. 2019. Induced energy-saving efficiency improvements amplify effectiveness of climate change mitigation. *Joule* 3(9):2103–19

178. Allan G, Hanley N, McGregor P, Swales K, Turner K. 2007. The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom. *Energy Econ*. 29(4):779–98

179. Turner K. 2009. Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Econ*. 31(5):648–66

180. Lemoine D. 2018. *General equilibrium rebound from energy efficiency innovation*. NBER Work. Pap. 25172

181. Fullerton D, Ta CL. 2019. *Costs of energy efficiency mandates can reverse the sign of rebound*. NBER Work. Pap. 25696

182. Rausch S, Schwerin H. 2018. *Does higher energy efficiency lower economy-wide energy use?* CER-ETH Econ. Work. Pap. Ser. 18/299

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Annual Review of
Environment
and Resources

Volume 46, 2021

Contents

I. Integrative Themes and Emerging Concerns

Land Use and Ecological Change: A 12,000-Year History
Erle C. Ellis 1

Anxiety, Worry, and Grief in a Time of Environmental and Climate Crisis: A Narrative Review
Maria Ojala, Ashlee Cunsolo, Charles A. Ogunbode, and Jacqueline Middleton 35

II. Earth's Life Support Systems

Greenhouse Gas Emissions from Air Conditioning and Refrigeration Service Expansion in Developing Countries
Yabin Dong, Marney Coleman, and Shelie A. Miller 59

Insights from Time Series of Atmospheric Carbon Dioxide and Related Tracers
Ralph F. Keeling and Heather D. Graven 85

The Cold Region Critical Zone in Transition: Responses to Climate Warming and Land Use Change
Kunfu Pi, Magdalena Bieroza, Anatoli Brouchkov, Weitao Chen, Louis J.P. Dufour, Konstantin B. Gongalsky, Anke M. Herrmann, Eveline J. Krab, Catherine Landesman, Anniet M. Laverman, Natalia Mazei, Yuri Mazei, Mats G. Öquist, Matthias Peichl, Sergey Pozdniakov, Fereidoun Rezanezhad, Céline Roose-Amsaleg, Anastasia Shatilovich, Andong Shi, Christina M. Smeaton, Lei Tong, Andrey N. Tsyganov, and Philippe Van Cappellen 111

III. Human Use of the Environment and Resources

Energy Efficiency: What Has Research Delivered in the Last 40 Years?
Harry D. Saunders, Joyashree Roy, Inês M.L. Azevedo, Debalina Chakravarty, Shyamasree Dasgupta, Stephane de la Rue du Can, Angela Druckman, Roger Fouquet, Michael Grubb, Boqiang Lin, Robert Lowe, Reinhard Madlener, Daire M. McCoy, Luis Mundaca, Tadj Oreszczyn, Steven Sorrell, David Stern, Kanako Tanaka, and Taoyuan Wei 135

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

The Environmental and Resource Dimensions of Automated Transport: A Nexus for Enabling Vehicle Automation to Support Sustainable Urban Mobility
Alexandros Nikitas, Nikolas Thomopoulos, and Dimitris Milakis 167

Advancements in and Integration of Water, Sanitation, and Solid Waste for Low- and Middle-Income Countries
Abishek Sankara Narayan, Sara J. Marks, Regula Meierhofer, Linda Strande, Elizabeth Tilley, Christian Zurbrügg, and Christoph Lüthi 193

Wild Meat Is Still on the Menu: Progress in Wild Meat Research, Policy, and Practice from 2002 to 2020
Daniel J. Ingram, Lauren Coad, E.J. Milner-Gulland, Luke Parry, David Wilkie, Mohamed I. Bakarr, Ana Benítez-López, Elizabeth L. Bennett, Richard Bodmer, Guy Cowlishaw, Hani R. El Bizri, Heather E. Eves, Julia E. Fa, Christopher D. Golden, Donald Midoko Iponga, Nguyễn Văn Minh, Thais Q. Morcatty, Robert Mwinyihali, Robert Nasi, Vincent Nijman, Yaa Ntiamoa-Baidu, Freddy Pattiselanno, Carlos A. Peres, Madhu Rao, John G. Robinson, J. Marcus Rowcliffe, Ciara Stafford, Miriam Supuma, Francis Nchembi Tarla, Nathalie van Vliet, Michelle Wieland, and Katharine Abernethy 221

The Human Creation and Use of Reactive Nitrogen: A Global and Regional Perspective
James N. Galloway, Albert Bleeker, and Jan Willem Erisman 255

Forest Restoration in Low- and Middle-Income Countries
Jeffrey R. Vincent, Sara R. Curran, and Mark S. Ashton 289

Freshwater Scarcity
Peter H. Gleick and Heather Cooley 319

Facilitating Power Grid Decarbonization with Distributed Energy Resources: Lessons from the United States
Bo Shen, Fredrich Kahrl, and Andrew J. Satchwell 349

From Low- to Net-Zero Carbon Cities: The Next Global Agenda
Karen C. Seto, Galina Churkina, Angel Hsu, Meredith Keller, Peter W.G. Newman, Bo Qin, and Anu Ramaswami 377

Stranded Assets: Environmental Drivers, Societal Challenges, and Supervisory Responses
Ben Caldecott, Alex Clark, Krister Koskelo, Ellie Mulholland, and Conor Hickey 417

Transformational Adaptation in the Context of Coastal Cities
Laura Kuhl, M. Feisal Rahman, Samantha McCraine, Dunja Krause, Md Fahad Hossain, Aditya Vansh Bahadur, and Saleemul Huq 449

IV. Management and Governance of Resources and Environment

Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature
Eduardo S. Brondízio, Yildiz Aumeeruddy-Thomas, Peter Bates, Joji Carino, Álvaro Fernández-Llamazares, Maurizio Farhan Ferrari, Kathleen Galvin, Victoria Reyes-García, Pamela McElwee, Zsolt Molnár, Aibek Samakov, and Uttam Babu Shrestha 481

Commons Movements: Old and New Trends in Rural and Urban Contexts
Sergio Villamayor-Tomas and Gustavo A. García-López 511

Vicious Circles: Violence, Vulnerability, and Climate Change
Halvard Buhaug and Nina von Uexkull 545

Restoring Degraded Lands
Almut Arneth, Lennart Olsson, Annette Cowie, Karl-Heinz Erb, Margot Hurlbert, Werner A. Kurz, Alisher Mirzabaev, and Mark D.A. Rounsevell 569

How to Prevent and Cope with Coincidence of Risks to the Global Food System
Shenggen Fan, Emily EunYoung Cho, Ting Meng, and Christopher Rue 601

Forests and Sustainable Development in the Brazilian Amazon: History, Trends, and Future Prospects
Rachael D. Garrett, Federico Cammelli, Joice Ferreira, Samuel A. Levy, Judson Valentim, and Ima Vieira 625

Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve?
Isak Stoddard, Kevin Anderson, Stuart Capstick, Wim Carton, Joanna Depledge, Keri Facer, Clair Gough, Frederic Hache, Claire Hoolohan, Martin Hultman, Niclas Hällström, Sivan Kartha, Sonja Klinsky, Magdalena Kuchler, Eva Lövbrand, Naghmeh Nasiritousi, Peter Newell, Glen P. Peters, Youba Sokona, Andy Stirling, Matthew Stilwell, Clive L. Spash, and Mariama Williams 653

V. Methods and Indicators

Discounting and Global Environmental Change
Stephen Polasky and Nfamara K. Dampha 691

Machine Learning for Sustainable Energy Systems
Priya L. Donti and J. Zico Kolter 719

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.

Indexes

Cumulative Index of Contributing Authors, Volumes 37–46 749

Cumulative Index of Article Titles, Volumes 37–46 756

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://www.annualreviews.org/errata/environ

Annu. Rev. Environ. Resour. 2021.46:135-165. Downloaded from www.annualreviews.org
Access provided by University of California - Berkeley on 05/15/23. See copyright for approved use.