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Energy Efficiency: What has Research Delivered in the Last 40 years?

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

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Abstract

This article presents a critical assessment of research over the last 40 years 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, the role of innovation, and the influence of policy. After 40 years of research, energy efficiency initiatives are generally perceived as being 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 economic output and have been associated with net improvements in either welfare or emission reductions or both. Rebound effects at the macro level still warrant careful policy attention as they may be non-trivial. 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.

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Keywords

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

Key Terms/Definitions and Abbreviations

E	physical energy use (e.g., BTUs, Joules, GWh, Mtoes)
Q	useful outputs (e.g., lumens, passenger miles)
$\varepsilon = \frac{Q}{E}$	energy efficiency
$I = E/Q$	energy intensity
Y	real economic output (often real GDP)
$I = E/Y$	energy intensity
$Y = \lambda f(\pi K, \rho L, \tau E, \upsilon M)$	production function, where Y represents gross output, K, L, E, and M are capital, labor, energy and material inputs, respectively. $\lambda, \pi, \rho, \tau, \upsilon$ are exogenous, time-dependent multipliers representing technical change.

Summary Points

1. Over the past 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. (Section 2 and Figure 1).
2. Energy consumption per unit of GDP (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. (Section 3)
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), while imperfect, has proved extremely useful as a guide to R&D and to policy design (Section 2)
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 culture and norms justify policy intervention and innovation policies to improve energy efficiency. (Sections 4 & 5)
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. (Sections 5 & 6)
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. (e.g., lighting had a 10,000-fold improvement in lumens/Watt since the start of the industrial revolution). (Sections 4 & 6)

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. (Sections 4, 5, &6)
8. Rebound suppressing policies can harm disproportionally consumers experiencing energy poverty. (Section 6)
9. Understanding the overall outcomes associated with energy efficient strategies and policies requires cross-disciplinary and inter-disciplinary efforts that necessitate engineering, economics, and social science collaboration. (Section 4).
10. There are tradeoffs 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. (Section 6)
11. Methodological advances for examining energy efficiency effects on energy use have been substantial. Primary advances include randomized control trials coupled with appropriate econometric methods, development in econometric methods and lab/field experiments, agent-based modeling, general equilibrium methods, and behavioral science. No methodological approach has so far been shown to be unfruitful. (Sections 7 & 8)

Future Issues

1. There is need for more analyses of energy efficiency and its impact at various stages of development and in the context of complex systems where the outcome will not be the simplistic aggregate result of energy savings from individual efficient technologies, due to systems interactions. We also need analyses that value energy efficiency at social prices, and 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 run and longer term.
2. There is a need to further build the evidence base delineating outcomes from energy efficiency technologies, strategies and policies. Synthesis of randomized control trials 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 vs. macro domain, level of economic development, demographics, income distribution, likely growth in demand).
4. There is strong evidence that market failures and policy distortions are present leading to deviations between the theoretical and 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 co-benefits of energy efficiency particularly in terms of avoided or induced externalities from air pollution, climate change, congestion, and waste, to name a few.
6. There is 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 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 under 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 data sets available to the community, and to the extent possible, to include granular data that that follows key quantities of interest over time. Such new streams of data, while important, may still not be able to solve causality questions.
10. Methodology improvements and richer data sets will matter to the formulation of sound energy efficiency policies and greater confidence in deploying them.
11. As countries make pledges and adopt goals aimed towards 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, among other), which in turn has implications for optimal investments of energy efficiency and their distributional consequences.

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 (GHGs) and air and water pollutants, and to 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 occurs between the micro and the macro scale.

This journal has published several review articles on energy efficiency, typically focusing upon 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 US and Mexico [6]–[8]. In the 2000s, focus shifted to understanding the implications of regulatory mechanisms in terms of end use benefits as well as links to rebound effects [3], [8], [9]. In recent decades, the research interest moved towards 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 assess how this has influenced 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). Section 5 describes how policies evolved over time to drive efficiency improvements by energy users, and section 6 describes the outcomes of such policies, as well as the unintended consequences that need policy attention. Section 7 summarizes methodological advances for assessing energy efficiency outcomes. Finally, we offer some conclusions and suggest ways forward for future research in section 8. 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) as the inverse of this measure.

The relevant system may vary in the outputs it provides (i.e., light, heat, work, wealth, just to name a few) and in its scale (i.e., a lightbulb, a machine tool, a firm, a sector, or a national economy). Depending upon the system and purpose at hand, it may be appropriate to use thermodynamic measures (e.g. enthalpy, exergy), physical measures (e.g. vehicle kilometers, tons of steel, tons of oil), and/or economic measures (e.g. gross output, GDP, expenditure on fuel) of inputs and/or outputs [13]. Energy efficiency measures also differ in how they *aggregate* qualitatively different energy inputs (e.g. summing kWh in a productive process such as a factory or weighting by relative price) [10], [14], and how they *partition* energy inputs between multiple and co-produced 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 efficiency. The 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). The 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 the efficiency with which they are used as well as cost-effectiveness and profit/utility maximization. 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 all inputs, the costs of the inputs, the mix of outputs etc. Macro-economists often use an absolute measure, energy intensity, the ratio of primary or final energy consumption to GDP, as a proxy to the inverse of energy efficiency for a national economy. While 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 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, i.e., considering either all available technological options that would be used to improve efficiency, regardless of their cost (i.e., the *theoretical maximum engineering efficiency*), 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 and Stavins [23] propose two distinct notions. The technological optimum (or maximum) is achieved if all present barriers to adoption are eliminated, while the economic optimum refers to cost and addressing barriers that are market failures. Market failure can arise in the presence of public good features, or because there is information asymmetry, or the market is non-competitive, or due to externalities not represented by the market price, or due to unexplained behavioral characteristics, just to name a few. Policy distortions may also lead to the energy efficiency gap, such as subsidies or incentives for some technologies, or tax breaks for others.

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 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) are pursued. The social gap also explicitly includes benefits associated with having energy service markets working closer to ideal conditions and including 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, while imperfect, has proved extremely useful as a guide to R&D and to policy design.

At the level of countries, macro-economists often use the inverse of energy intensity (the ratio of primary or final energy consumption to GDP) as a proxy to energy efficiency for a national economy. While 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 IEA and other organizations have predicted [26].

Macro-economists 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* (*CEI*) 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 gross output and K, L, E, and M are capital, labor, energy and material inputs, respectively. $\lambda, \pi, \rho, \tau, \upsilon$ 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, since less energy is required to produce the same level of output, this should reduce aggregate energy intensity ($I=E/Q$), *ceteris paribus*. Energy-augmenting technical change (τ) provides one measure of energy efficiency improvements, 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 upon the level and price of each input ([unit] cost), the current state of technology and the level of output, as well as upon 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 non-energy 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 towards more energy intensive goods and services owing to a fall in their relative price.

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 policymakers 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. While 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 difficulty to define as systems boundaries increase and become more complex. This also leads to more uncertainty regarding the outcome 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.

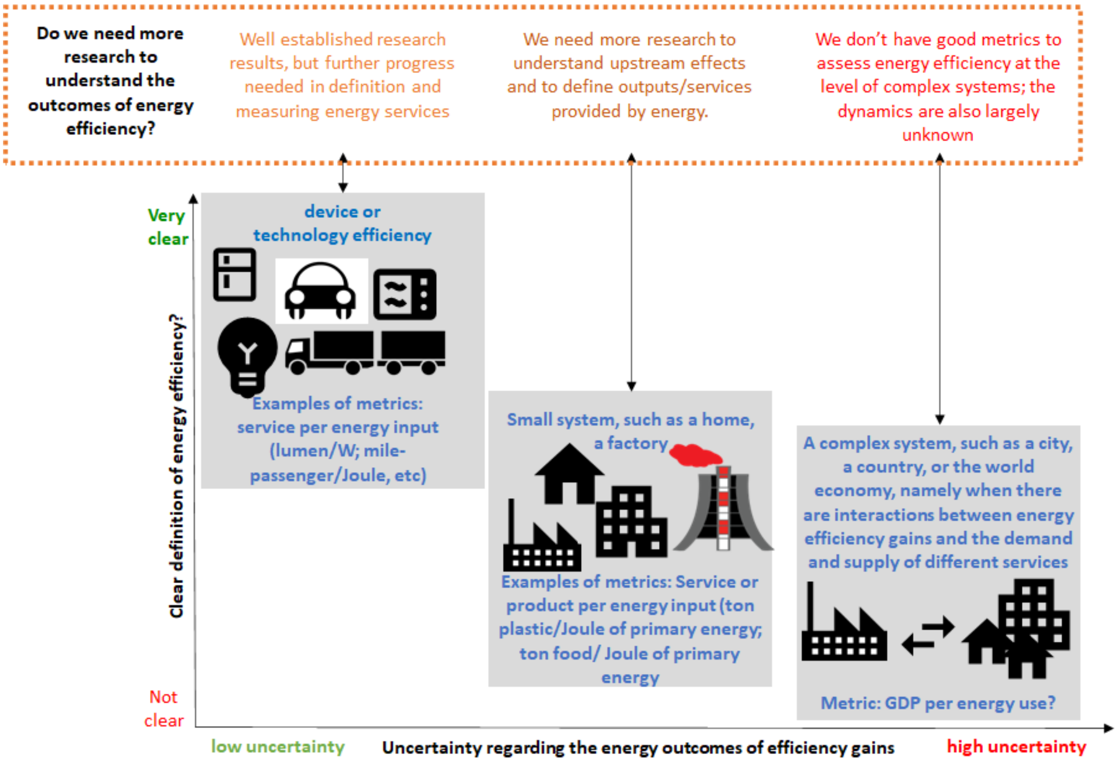

Figure 1: Energy efficiency: Domains of knowledge and of different energy efficiency definitions.

3. Historical Trends

Energy intensity trends have been widely used to represent progress in energy efficiency for practical policy purposes and decision making (e.g., IEA. Energy efficiency market report 2019 [32]) due to its simplicity. 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 inverse U-shaped curve of energy intensities in the long run [33]. As shown in Figures 2a and 2b, energy intensity appears to rise with industrialization and then decline.

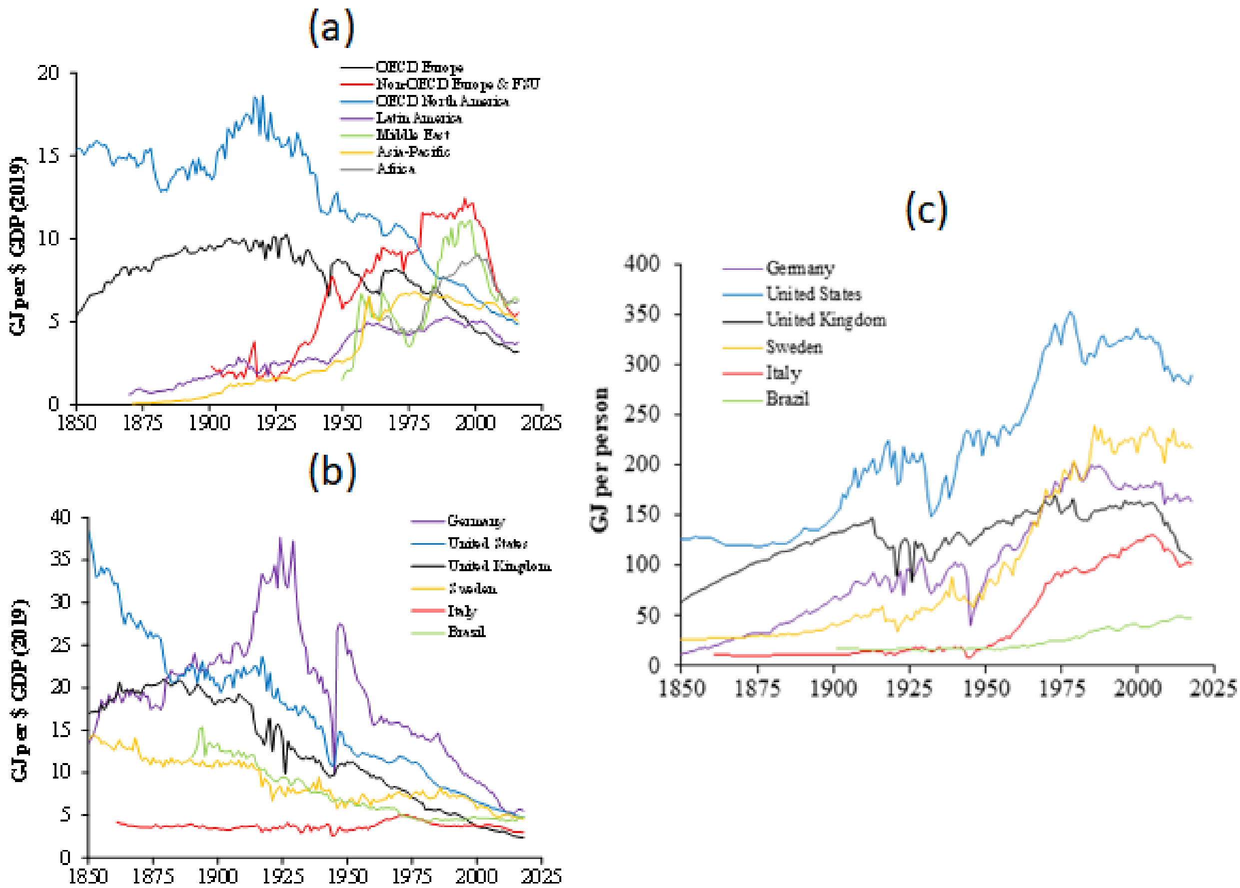

Figure 2: (a) Energy intensity for regions of the world, including only modern energy sources and excluding traditional energy sources (1850-2016); (b) Energy intensity for major economies, including traditional and modern energy sources (1850–2016); (c) Energy consumption per capita for major economies, 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]**.**

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. Energy intensity changes 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. Figure 2(a) suffers from this limitation whereas Figure 2(b) and Figure 2(c) do not. Thus, a richer story emerges - in which certain economies, such as the UK and Germany, who benefited from large coal deposits, but limited traditional energy sources, experienced inverse-U shaped trends. Others, including the United States, Sweden and Brazil, with abundant traditional energy sources, 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 within industries appears to be responsible for more of the decline in energy intensity globally than broad structural change [26]; e.g. the UK economy saw a c.30-fold increase in steam engine efficiency from 1750-1850, and a further c.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. While 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 GJ/GDP) across some regions and countries is narrowing [43], [44] – see also Figures 2(a) and 2(b); this convergence has taken about a century since 1850. Economies tend to broadly converge at high levels of per capita income – and reductions in energy intensity come in tandem with increases 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 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 and finds that the two latter 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 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 towards more energy intensive goods – a rebound effect. Based on 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 the remaining gap is explained by income effects encouraging consumption patterns to shift over time towards more energy-intensive goods [46].

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 of per capita energy consumption. This, in part, reflects the differing trends in the energy intensity metric and energy per capita metric. While energy intensity has declined over 170 years by a factor of 3-8 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 those [47]. Others claim that market failures warrants 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]. These include misplaced incentives [49], imperfect information [49], [50], decisions influenced by habit and non-perfect substitutability [49], negative externalities [26], [50], bounded rationality [50], uncertainty [49], transaction costs [49], [50] and lack of access to financing [48], [49].

A number of failures have been proposed in the literature [51], which could be summarized as non-market failures or disincentives to adoption, specific market-failures, and unexplained behavioral characteristics . Non-market 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 of 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 towards "hassle" costs that, while 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 (such as unpriced environmental externalities and average-cost pricing), information market failures (asymmetric information and principal-agent problems), capital market failures (such as credit constraints) and innovation market failures (arising from research and development spillovers where innovating firms cannot capture the full benefits of their efforts) [16], [52]. While evidence of certain market failures is persuasive, in particular 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 energy use studies, 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 behavioral characteristics (sometimes dubbed "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 and using 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 economic studies have revealed a variety of behaviors that can potentially explain the gap. Randomized Controlled Trials (RCT), which are the gold standard for identifying causal effects, have shown how these divergences can drive individuals to behave in a way that led to sub-optimal 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 labelled as failures, which in turn provides additional rationales for energy efficiency policy [56]. However, much more empirical research is needed to determine if unexplained anomalies do in fact cause systematic deviations between decision 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 understand now 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 poor construction of 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 and Dowlatabadi [58] expand the somewhat siloed thinking on energy efficiency and consumer decision making by presenting a range of frameworks, ranging from the neo-classical and behavioral economics, through 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

Types of policies

Over these four decades several types of policies to improve energy efficiency and conservation have evolved, been implemented, and 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. With due limitations, below we summarize the existing knowledge for both traditional policies (e.g. efficiency standards, information and labeling programs) and relatively new, more recent behavioral-oriented interventions (e.g. social norms, rewards).

Appliance and equipment efficiency standards and building codes: The most widely used policy over these four decades has been energy efficiency standards for appliances and equipment [59]. Standards have been widely used in the US since the 1970s [59], [60] starting 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 EU [61] , China [62], 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 (e.g., [65], regarding refrigerators standards in the U.S.) while 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 in tension with and substantially offset by other factors including vehicle mass, engine power, acceleration and occupant-safety. However, the relative contribution of prices vs. standards in econometric studies depends on the period, study design, and region (e.g. contrast [68] and [69]). Newell et al. [70] found energy efficiency regulations in the

US 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].

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 U.S. Environmental Protection Agency (EPA) has had a very big impact for some products [60] but is also very popular now in almost all countries. Combined with higher energy prices, Newell et al. [70] found that labeling requirements encourage the production of more energy-efficient products.

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, tradable certificates, etc. 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].

Providing feedback to consumers: The advent of advanced metering infrastructure (AMI) in the last decade enabled consumers to have regular and detailed information on energy consumption. However, researchers found that consumers were confused about what smart meters were and their functionalities as AMI was expanding [77]. The provision of direct feedback has long been used by utilities and authorities to promote energy efficiency, with mixed results. On the one hand, 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 question 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 wouldn't 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 to best performing or average use of similar households [62]. The evidence shows that the use of social norms is (cost-) effective in 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].

Pledges or commitments: These pledges or commitments are "promises to change behavior" [88] related to energy use "that allow individuals to lock themselves today into the action that they want to take tomorrow" [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].

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 in 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 range from 3% to 20% energy reduction, but with results being highly context-dependent [54]. Policy distortions or failures (such as the lack of policy action, subsidies, incentives or taxes for non-efficient energy strategies) can also affect the outcomes. Policy complementarities and the level of ambition (e.g. via stringent energy saving targets) appear to be critical determinants for significant impacts.

Evidence of direct benefits

Assessing the impact of policies on outcomes - *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 an energy reduction associated with energy efficiency labels and standards on the efficiency of household appliances, lighting, building efficiency, vehicles, and motor drives. For example, the Energy Star" labeling program run by the U.S. Environmental Protection Agency (EPA) has had a very 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 100TWh (lifetime impact). However, the diversity of sources – including ex-ante Regulatory Impact Assessments – means the underlying methodologies are varied.

When assessing the outcomes of several energy efficiency programs (programs including building codes, product standards, subsidies, information provision and weatherization and behavioral interventions), Gillingham et al. [54] find that estimated energy savings range from 0-24 percent 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 evaluation of instruments targeted at business and public sector energy use in the UK find significant savings: the climate change levy and related climate change agreements demonstrated an 'announcement' effect with more enduring induced energy savings of around 5%/yr [100], whilst the CRC energy efficiency scheme, which required organizations to report and buy allowances to cover their direct and indirect emissions, reduced CO2 emissions by 6-8% (with gas savings greater than electricity savings), some three times the ex-ante estimate probably because of the way it combined economic and non-economic incentives [101].

Cost-effectiveness of energy efficiency programs:

Cost-effectiveness ranges from 1.1 cent per kWh for behavioral programs to 50 cents and higher (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 [98] also finds wide variation, with cost savings mostly in the range 1-6 USc/kWh in western Europe and US, but often over 10USc/kWh in eastern European countries. Bento et al. [102] find that certain vehicle efficiency standards provide benefits exceeding costs. Measured cost-effectives can be lower for low-income households [103], but recent work has confirmed that rebound can also be stronger for those households [104], [105]. It has also been demonstrated that energy savings from similar measures can vary significantly depending on income and household deprivation, with lower income households saving less [106] but likely receiving other non-measured benefits. These results emphasize that any welfare calculation is incomplete unless a wide set of benefits is considered.

6. Wider Consequences of Energy Efficiency Policy

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

Evidence of indirect benefits

A number of authors have attempted to estimate the non-energy benefits of energy efficiency [61], [107]. Ürge-Vorsatz categorizes these as comprising health effects, ecological effects, economic effects, service provision benefits and social effects [61] and the IPCC shows energy efficiency synergies with Sustainable Development Goals (SDGs) [108]. An IEA study identified some 15 social welfare-creating outcomes that are, or may be, beneficiaries of energy efficiency improvements [107]. These include "various macroeconomic benefits (e.g., shifts in energy trade balances and employment), increased access to energy and improved affordability of energy services, reduced air pollution, and fiscal improvements for national and sub-national entities." 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 co-benefits in the form of reducing negative externalities. For example, if an efficiency measure reduces the use of fossil fuels, there will be co-benefits from such measure in the form of reduced climate change impacts from greenhouse gases and reduced health damages associated with ground-level emissions of air pollutants [110], [111].

Chan and Gillingham [18] demonstrate using a micro-economic framework the conditions under which energy efficiency is welfare-enhancing. Azevedo [3] takes a broader perspective calling for a multi-objective 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, and whether cost-effectiveness includes estimates of the social cost of carbon [51], [53], [54], [112], and the co-benefits or costs that are induced by changes in externalities. It has proven very 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 UK, consumer surplus rose substantially during key energy transitions involving energy efficiency.

One geography with good data is the US, and for this reason much of the previously published academic work has been conducted there [57]. Gillingham, Palmer and co-authors have undertaken a couple of extensive reviews of this literature [54], [58]. Gillingham et al. [54] estimate an aggregated net saving of 2.8 cents per kWh from energy efficiency, which compares favorably to the marginal social cost of electricity generation, estimated at 5.6 cents per kWh (both in 2015 USD). Billingsley et al. compile data on over 1700 programs reported to US state regulators from 2009-2011 and find the average levelized cost for energy savings to be 2.1 cents per kWh in 2012 USD, with significant cross-sectoral variation [105]. Meanwhile in Europe, a number of studies have estimated the cost per kWh saved to range from 0.4-1.1 eurocent in 2008-2015 EUR [24].

Rebound effects

A notable development over the last 40 years has been the persistently re-emerging debate over "rebound effects." "Rebound" 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], and then resurrected in the literature by Brookes [114] and Khazzoom [112] in the 1970s, rebound effect were then studied by Grubb, Saunders, Pearson & Fouquet, Roy, and Lowe [115]–[119], and a number of other contributors that can be found in the seminal volume edited by Schipper [120]. More recent contributions arose from Azevedo [110], 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 rebounds. "Direct" rebound effects *are those directly related to the use of physical energy itself at the end point.* "Indirect" rebounds *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 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.

Researchers have reached different conclusions regarding the magnitude of rebound effects, in part given the different scope of analysis, 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") [111] [124], [3], [129], [130], [131] where 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 in fact they are referent to quite different issues. Azevedo [110] showed how ease of substitution by consumers across energy and non-energy 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 (CES), with the latter bring 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 macro-economic 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]. Fouquet and Pearson [117] propose that the resolution of "Jevons Paradox" is to appreciate that rebound effects vary at different levels of economic development and rebound magnitudes in early stages of development are likely to present as backfire. These macro-economic studies often use energy intensity as a proxy for energy efficiency. Stern [26], in a study across 87 countries and 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 (Stern [136], owing perhaps to underestimates of rebound effects, which Stern shows may approach 100% economy wide [126]), 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, when observing energy intensity trends, of considering the trends of other inputs to production, and their impacts on both output and energy use. Non-energy technology gains matter: Non-energy 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 labeling all these effects together under one homogeneous category of "rebound" and instead identify them by the processes and contexts giving rise to them. While in some cases "rebound" suppressing policies will be helpful in realizing reduced energy use from energy efficiency programs, in others a wider impact of providing affordable access to energy might appropriately cause policy makers to sacrifice some energy use reduction potential from technology deployment in favor of affordable access and a minimum level of per capita energy consumption, in developing countries especially [112].

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 happen 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-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 [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 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] show 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%.

Distributional effects

As described previously, historically energy intensity seemed to depend on the stage of economic development. Unless the energy is supplied from carbon-free sources, the GHG emissions intensity will also be higher in 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 tradeoff between economic well-being and climate change mitigation. The trade-off is different between rich and poorer countries. 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], 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 "In developing countries rebound suppressing policies cannot help in achieving affordable access to energy (Strategic Development Goal SDG 7 – 'Affordable and Clean Energy') faster, so rebound suppressing policies can harm disproportionally consumers [experiencing] energy poverty."

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 non-carbon 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 with actual savings and net benefits. Further, while RCTs are considered to be the gold-standard, for some policies it's simply not possible to implement them and studies have also criticized RCTs methods [143]. To further build the needed evidence-base and better understand the factors that affect energy efficiency outcomes, improved synthesis of multiple RCTs and other empirical methods is needed 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 saw a 10,000-fold improvement in lumens/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 appear to have induced innovation both directly, via their impact on the [U.S manufacturing firms'] own energy costs, and indirectly via their impact on customers' costs."

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 of evidence on induced energy innovation summarizes the results of 19 papers which 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, with one exception, studies of *building* technologies do *not* find that prices induce patenting [146] except in some cases for 'portable' technologies – e.g., small appliances, and "white goods" [147], suggesting a central problem of principal-agent and related barriers [148].

Experience or learning curves track how prices of technologies change as more units are produced or used. Weiss et al. [149] find an average, cross-technology learning rate – the cost reduction associated with a doubling of market–size - of 18% (±7%) across fifteen technologies (mostly building and appliance-related). However, rates of 20-30% were found for consumer electronics and components, heat pumps, and compact fluorescent light (CFL) technologies, with high learning in CFLs (in particular) reinforced by several subsequent studies. Rubin et al. [150] 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 goes along with the adoption and diffusion of technological innovation. Indeed, the World Bank defines innovation largely in terms of developing country adoption of known but under-utilized technologies. Two major reviews of the Porter Hypothesis - that environmental regulation can enhance firm competitiveness – find positive evidence [151], [152], and a major factor appears to be organizational as well as technological innovation in response to regulatory pressures. Among other factors this 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 (ETS) [153], [154] have emerged. Rogge, Schneider, & Hoffmann, [154] report that its introduction did indeed accelerate R&D activities within regulated firms, largely focused on CCS and energy efficiency. Gulbrandsen & Stenqvist [155] 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 as to how much of the observed improvement in national energy intensities shown in Fig.2 can be attributed to induced innovation becomes harder to disentangle from numerous other factors including composition and other structural changes. Steinbuks & Neuhoff [156] 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 [157] decompose aggregate energy demand in Canada into a scale, composition, and technique (intra-sectoral energy intensity changes) partitioning and find some evidence of price-induced innovation. Sue Wing [158] finds that up until the 1970s energy price shocks, innovation was energy-using and almost exclusively exogenous. In contrast, over the period 1980-2000 technical change became energy saving and towards 2000 ultimately 40% of total (disembodied) technical change can be attributed to induced technical change ([158], Figure 7). Finally, Carraro & De Cian [159] 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, Hourcade and Neuhoff [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, whilst 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 [160] analyze 15 OECD countries over 49 years, finding statistically significant evidence for a *combination* of both stochastic exogenous trends, *and* asymmetric price responses, robustly finding "both endogenous technical progress and an exogenous underlying energy demand trend."

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; 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 for 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.

Frontiers in energy choice modeling: In the context of understanding consumer choices and behavior, the discrete-choice methods developed by Hausman [161] 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 have enabled authors to overcome this limitation by eliminating unobserved costs, in the study of vehicle adoption decisions [162]. Other applications of methods have emerged, such as the use of agent-based model to simulate the behavior of industry agents and consumer agents [163] regarding lighting choices [164].

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 has been developed that helps the analyst infer causal relationships from data [165]. A key concern in program evaluation is the ability to identify adverse selection and infra-marginal participants (or free-riders). Boomhower and Davis [166] use Regression Discontinuity to estimate infra-marginal participation in energy efficiency subsidy schemes, while Alberini and Towe [167] combine statistical matching with panel fixed-effects estimators to compare the benefits of information provision with energy efficiency incentives. While these methods are useful, the gold-standard for empirical policy evaluation is the RCT. This method has been applied extensively in evaluation of energy efficiency interventions [52], [53], [143]. The approach is not without its critics and some concerns have been raised about the external validity of results [168]. One of the single most important advances in the understanding of energy efficiency outcomes has been combinations of the implementation of large scale RCTs , coupled with advances on econometrics, data analysis and statistics. This has been crucial to better understanding the outcomes of energy efficiency related policies and programs.

The development of RCTs, new large field experiments and new data analysis techniques has shed come lights on 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 percent, the average rate of return on such investment is -7.8%, even when accounting for the environmental benefits of emission reduction. Importantly, both the private and social rates of return are positive when calculated using the ex-ante predicted savings, suggesting a need for better policy design and evaluation. Despite the target group in this instance being low-income households, 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 point in time, could be considered one estimate of direct rebound. Others, 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 [169] use a large field experiment that imperfectly targeted and calibrated subsidies can 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.

Recently, machine learning (ML) techniques have been applied to both observational and experimental data. A particular appeal of these 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 for energy efficiency upgrades in schools, outperforming standard panel-fixed effects approaches [170]. Additionally, ML methods are useful for estimating heterogenous treatment effects and have been applied by a number of researchers in this regard, in particular, on high-dimensional smart metering datasets [171], [172]. The quantification of heterogeneity is important in improving targeting of information, subsidies and other types of policies in order to increase their welfare impacts [172]. 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 an economic entity is from the optimum, or production frontier. This method has been used to examine underlying energy efficiency at a range of scales in the US, EU, OECD [173], and in developing countries[174].

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 [175], 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 sectoral level and finds large factor substitution elasticities and rebounds in many US sectors. Wang et al. [176] find evidence for energy that the technology parameter (factor efficiency gain) can be econometrically estimated and thus can be 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, general equilibrium (GE) is used as it computes equilibrium for all markets at endogenously calculated prices. Allan et al. [177] first introduced computable general equilibrium (CGE) modeling to the exploration of energy efficiency gains on energy use. Wei [132] followed with a theoretical GE formulation he used to develop analytic conditions around the efficiency/energy use interaction. Turner [178] used CGE modeling to discover a "disinvestment effect" that leads to lower energy use. Lemoine [179] developed a very generalized GE framework that allows for an indefinite number of producers and consumers, and confirms that flexibility of the economy is key to understanding how efficiency gains affect energy use – both flexibility in and among producers to substitute factor inputs, and flexibility of consumers to adjust their demand profile among multiple goods and services offerings. Fullerton and Ta [180] developed a general equilibrium model that embeds a general expression for household utility and use this to explore the effects of exogenous changes in energy efficiency.

There is deep need for further empirical analysis to create more definitive conclusions about the efficiency/energy use dynamic. For instance, Lemoine's 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 be tied to functional forms for consumption that allow substitution among products demanded. For a fuller picture, general equilibrium methodologies further need to incorporate time dynamics of the type found in neoclassical growth models as in the manner of Rausch and Schwerin [181].

9. Conclusions

Deploying energy efficiency is necessary and one of the key strategies needed to achieve climate change mitigation, 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 energy efficiency's role 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. While all these aspects may be described under the umbrella of "energy efficiency" research, they in fact are looking at very different but often intertwined effects. Indeed, across fields and research topics, many 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 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, while at the device level it is trivial to define efficiency metrics, 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 being a very 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 damages 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 a new resulting 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 onto energy efficiency questions. Examples of such endeavors include: (i) at the micro-level, a better understanding of consumer choice and behavior by combining insights from engineering and the advanced metering and sensing infrastructure, with those from micro-economic theory as well as the theory of choice and with behavioral economists' models; (ii) at the program evaluation level, there is a need to continue to develop methods to understand causal inferences using econometrics as well as machine learning to better understand program outcomes; (iii) at the macro-level, developing flexible and credible general equilibrium models that also 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, are needed.

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