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The history of energy efficiency in economics: Breakpoints and regularities

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ABSTRACT

Taking a long-run historical perspective, we analyze how debates about energy efficiency have evolved in the economic literature since the mid-19th century. We distinguish three periods: the classical age, focused on the rebound effect, from Jevons in the 1860s to American institutionalism in the mid-20th century; the modern age, marked by the rise of the energy efficiency gap concept, from the 1970s to the 1990s; the contemporary age, from the early 2000s onwards, focused on the concept of energy performance gap. We find that reflections on energy efficiency have embraced more general developments in the economics discipline: emergence of institutionalism in the classical age, primarily concerned with policy; public economics in the modern age, emphasizing the concept of market failure; behavioral economics and the so-called credibility revolution in empirical economics in the contemporary age, which made energy efficiency a much-favored context for conducting experiments, questioning rationality and implementing nudges. The transitions between phases closely paralleled changes in societal concerns, from resource depletion in the classical age to energy security in the modern age to climate change in the contemporary age. Throughout this long history, we have detected a change in focus from macro- to micro-perspectives. Despite increasing sophistication and constant reinterpretation, energy efficiency remains a subject of controversy, such that no consensus has yet been reached on its potential and effective benefits. In closing, we propose to update Jaffe, Newell and Stavins' landmark energy efficiency gap framework to account for the most recent developments and trace avenues for future research.

0. Introduction

Energy efficiency is considered to offer tremendous opportunities for climate change mitigation as well as important co-benefits such as increased comfort, productivity gains, resource conservation and a lower dependence on foreign energy sources. Technically, energy efficiency is a component of the broader notion of energy service, i.e. "those functions performed using energy which are means to obtain or facilitate desired end services or states" [1]. Produced by general-purpose technologies [2,3], energy services virtually underpin any single activity in the economy. In this framework, energy efficiency can be defined as the ability of a technology to minimize the quantity of energy input (e.g. kWh, MJ, etc.) needed to produce a given level of energy service (e.g. lumen, temperature, passenger.km, etc.).[1]

Primarily a technological characteristic, energy efficiency becomes an economic concern as one recognizes the upfront cost of the technology, the energy operating costs it is supposed to alleviate and the benefits consumers derive from the associated service—in other words, as one views energy efficiency as an investment. The economic perspective is all the more important to consider that it has pervaded energy efficiency policy, which nowadays rests on a variety of economic instruments—energy efficiency subsidies, energy taxes, energy performance certificates, information disclosure (such as energy performance certificates), energy saving obligations. Yet the economic conceptualization of energy efficiency has been ever-changing throughout its long history, at least from William S. Jevons's seminal contribution (*The Coal Question*, 1865) to the most recent debates on climate action. Our goal in this paper is to pin down how, why and to what extent has the economic perspective on energy efficiency changed over time.

Taking a long historical perspective spanning a century and a half, we focus on three episodes: what we refer to as a classical age, running from the first known economic analyses of energy efficiency in the mid-

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[1] Energy *conservation* can also be found in the literature, sometimes used interchangeably with energy *efficiency*. Energy conservation is in fact broader, encompassing both energy efficiency improvements and behavioral change. Yet as energy *efficiency* is more common, we stick to this term in the paper.

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19th century, into the first half of the 20th century; a modern age, spanning the second half of the 20th century; and a contemporary age, starting in the early 2000s. Such an extensive time frame allows us to make connections between episodes that have hitherto been considered separately, either in historical research [4–6] or in more recent surveys [7,8].

We find that the transitions between the three ages of the economics of energy efficiency have espoused simultaneous changes in both societal concerns and the general economics discipline. Primarily concerned with the availability of energy resources (coal in particular), the economic debates of the classical age have given rise to the rebound effect concept, soon within an institutionalist framework that was typical of the early 20th century. In the wake of the first oil crisis, the modern age shaped the energy efficiency gap concept within a public economics framework that was then at the forefront in general economics. The contemporary age, characterized by a growing concern for climate change, has embraced two important trends in the general economics discipline, namely an increased attention to departures from the perfect rationality assumption (i.e. behavioral economics) and an increased concern with testing empirical predictions in the field (i.e. the so-called credibility revolution). These sequential changes unfolded within a broader shift from a predominantly macroeconomic perspective on energy efficiency in the classical age to an increasingly microeconomic perspective in the modern and contemporary ages. Yet despite these changing views, we note a striking regularity in that all economic debates on energy efficiency have not allowed key controversies (e.g. Does efficiency reduce energy use? How large in the rebound effect?) to be resolved.

Taking stock of these results, we close the paper by proposing an extended framework for the economic analysis of energy efficiency that includes more markets (credit and real estate markets in particular) and more processes (behavioral in particular). Recognizing that, as a general-purpose technology, energy efficiency is also related to technology, institutions and cultural habits, our economics-focused contribution complements prominent analyses of energy efficiency in other disciplines, such as sociology, institutional change, geography, energy history, and Science and Technology Studies (STS) (e.g. [9–19]).

The rest of the paper is organized as follows. Section 1 is devoted to the *classical age* of energy efficiency in economics, with a focus on the rebound effect, from Jevons in the 1860s to the mid-20th century. Section 2 characterizes the *modern age* that gave rise to the energy efficiency gap concept throughout the 1970s–1990s. Section 3 analyzes the *contemporary age* focused on investigating the energy performance gap with behavioral and empirical tools since the early 2000s. Section 4 proposes a conceptual framework, updated from Jaffe, Newell and Stavins's 2004 diagram [20], to summarize the results of our inquiry.

1. The classical age (1860s-mid-20th century)

The economic analysis of energy efficiency is usually considered to have started in the mid-19th century, when a better understanding of thermodynamic principles allowed production processes to be more efficient.[2] With the industrial boom of the late 18th century and early 19th century, energy—in particular the use of fossil fuels (peat, coal, gas, oil)—became a key topic of interest for observers, including economists. The first age of energy efficiency economics was thus characterized by a predominantly macroeconomic perspective on aggregate production and a concern for natural resource scarcity.

It is well known that W. Stanley Jevons made a decisive contribution to the matter with his book *The Coal Question* (1865), in which he expressed concerns about the future of British industrial development in a context of high dependence on increasingly scarce coal reserves [23–33]. It is also well established that Jevons laid at the same time the corner stone for the conventional economic analysis of energy efficiency, by highlighting a paradox later be known as the rebound effect [34,35].[3] In the 1860s, Jevons's reasoning on energy efficiency was still sketchy but it already pointed to problematic effects:

> "But no one must suppose that coal thus saved is spared – it is only saved from one use to be employed in others, and the profits gained soon lead to extended employment in many new forms. The several branches of industry are closely interdependent, and the progress of any one leads to the progress of nearly all." [38]

Sieferle [36] reports that, from the late 18th century to the mid-19th century, many observers produced estimates of the future of coal reserves. Most of them considered that enough fuel was available to meet demand for centuries to come. In sharp contrast, Jevons forecasted an exponential increase in fuel demand soon putting coal reserves under pressure. In his view, efficiency improvements would only make things worse.

It is rarely noted in the history of energy analysis that the impact of technological improvements in the coal sector remained a controversial issue into the late 19th century, long after Jevons's original publication. In 1878, Anthony J. Mundella [39] gave a talk at the Statistical Society, expressing his trust in the ability of new technologies to delay exhaustion. Jevons, together with a few other participants in the meeting, responded with skepticism. In the same year, John Marshall [40], professor at Yorkshire College, shed a new light on the tension between technological improvements and market mechanisms by stressing that economic maximization was seldom directed towards savings. He was also among the first to call for empirically estimating the relationship between energy efficiency improvements and energy savings. In France, economist Yves Guyot [41] embraced Jevons's position, noting that despite major improvements in fuel efficiency, production processes were using considerably more fuel than they once did. In contrast, in the 1890s United States, the former president of the American Institute of Mining Engineers, John Birkinbine, dismissed market processes and rather insisted on the role of technologies as a key driver in fuel market forecasts [42], which goes to show that consensus was lacking among observers in the late 19th century.

In 1915, Herbert S. Jevons, W. Stanley's son, wrote a comprehensive book on *The British Coal Trade*, in which he documented technological improvements in fuel supply and the emergence of new forms of power, such as electricity [4,29].[4] Referring to his father's book, he pointed out that the energy efficiency gains of the late 19th century did not permit a reduction of coal consumption, not even on a per capita basis [43]. H. S. Jevons's book did not leave a strong mark on the history of economics, but it was recognized as an important contribution at the time, as illustrates Alfred Marshall's mention of it in his *Industry and Trade* [46].

In the United States, the so-called Jevons paradox continued to be discussed in the 1920s, half a century after *The Coal Question*. It was then agreed that technologies and markets should be taken together to elaborate sound resource management programs [47]. In the late 1920s, the Brookings Institution in Washington, D.C. started a research project on the role of energy in economic development, taking an institutionalist approach which was the new mainstream at the time [48–50]. Participants in the project suggested that the field of mineral economics should be defined as the intersection between economics, geology and

[2] Then focused on firewood, the question of a proper use of energy resources was even discussed before industrialization [21,22]. We however confine our attention to the industrial era.

[3] Sieferle [36] reports that Sedgwick provided a preliminary version of the rebound mechanism before Jevons. Alcott [37] reviews economic writings sketching rebound effects before Jevons, but these focus on goods and services outside the energy sector.

[4] Generally speaking, in the first decades of the 20th century, the development of electricity had a clear impact on the perception of energy issues (see [44,45]).

engineering [51,52]. Mobilizing the different approaches however proved more difficult than expected, individual views often remaining anchored in technological or alternatively market perspectives [53]. On fuel efficiency, economists involved in the project started to conduct empirical analysis, noting that the First World War had generated important energy efficiency gains, yet with uncertain effects on total energy consumption [54].

This episode shows that an enduring critical tension was identified between technical progress and market mechanisms, with ambiguous, if not detrimental, effects of energy efficiency gains on total energy consumption. The emergence of American institutionalism led to a shift towards more empirical and policy-oriented research without changing the key insight: market incentives tend to mitigate efficiency gains.

This tension was revisited half a century later by Len Brookes [55] and Daniel Khazzoom [56], who framed the lack of proportionality between energy savings and energy efficiency improvements in terms of *rebound effect*. An important effort followed to give structure to the concept and empirically estimate its various dimensions. As a result, rebound effects are by now considered to take different forms, depending on the range of energy services they involve [57,58]. The *direct* rebound effect consists of a more intensive use of energy services caused by energy efficiency improvements on the underlying technology. This occurs for instance when a more efficient car is used to travel longer distance. The *indirect* rebound effect refers to a more intensive use of an energy service following efficiency improvements on technologies providing a different service. The canonical example is that of households saving on heating expenditure thanks to insulation investment and thus spending more on energy-intensive activities—typically air travel. The *macroeconomic* rebound effect results from the interplay between direct and indirect rebounds at the aggregate level. A contemporary example is the spread of (energy-consuming) smartphones permitted by energy efficiency gains in production lines [59].

While the different effects are clearly defined, empirical estimates widely differ as to their magnitude [35,58,60]. Most direct effects are found to be within the 10–30 % range [61,62]. The indirect and macroeconomic effects tend to be larger, though methodological challenges prevent them from being precisely estimated. A debated issue is whether 'backfire' rebound effects—efficiency improvements resulting in net increases in energy consumption, as Jevons pointed to—are empirically relevant. After decades of research into the issue, estimates of the rebound effect continue to vary widely. Some studies point to rebound effects mostly confined below 50 % [62] while others find they consistently exceed 60 % [60]. Energy efficiency improvements are most likely to backfire with general-purpose technologies in fast-growing economies [35]—precisely the kind of situation that was studied by Jevons in relation to the steam engine during the Industrial Revolution [63] and which is nowadays happening with information technologies [59].

Today, the issue remains controversial, despite claims that it is settled. In 2016, the editors of *Energy Policy*, a major outlet in the field, ranked "energy rebound analysis" third among a list of five topics for which "the intellectual contribution of most of the recent papers […] has been slight" [64]. The editors added that they were "limiting consideration of new manuscripts in these five research areas to those few manuscripts that are sufficiently unique that they make a significant contribution to the literature and policy guidance." As a matter of fact, a search for "rebound effect" in *Energy Policy* returns positive results for 5 % of the papers published in 2016, 5 % in 2017, 5 % in 2018, 8 % in 2019 and 9 % in 2020, suggesting that, despite editorial changes, the issue continues to receive widespread attention.

2. The modern age (1970s–1990s)

The classical age of energy efficiency in economics gradually phased out between the 1930s and 1970s. The affordability of energy in the post-war era favored an extensive use of energy resources, with little concern for energy efficiency, except in a few research programs [4,65]. The energy efficiency issue did not stand out from the broader energy analysis. Even that field, despite using increasingly more sophisticated methods, such as econometrics, did not produce major advances—it was not until the 1960s that Hotelling's 1931 model of exhaustible resource extraction [66] started being used to produce major breakthroughs, especially in the examination of fossil fuels [67–70].

The state of the art changed quite significantly in the late 1970s in the wake of the oil crisis. In the early ages of mass consumption era, energy use had become a concern for households as much as for industrial sectors. Energy efficiency policies became widespread, in particular in the United States through so-called demand-side management (DSM) programs rolled out between 1975 and 1978 in many States. Primarily motivated by energy security, the rationale of DSM programs was to rely on electric and gas utilities to leverage their knowledge of energy end-use patterns and associated savings potentials. Alongside the rebound effect, a new concept emerged: the energy efficiency gap. Just like the rebound effect, it started with a controversy between technology-oriented and market-oriented views on energy efficiency [71,72].

On one side, technology advocates such as Amory Lovins and his group at the Rocky Mountain Institute came to prominence by extolling the virtue of energy efficiency, "not a free lunch; […] a lunch you are paid to eat" [73].[5] On the other side, market-inclined observers expressed skepticism, arguing that there must be a reason for agents not investing in efficiency improvements. In that vein, William D. Nordhaus wrote in 1991:

> "[…] it seems technically feasible *in principle* to increase energy efficiency […] at little or even negative social cost. In the colloquialism of economics, this analysis suggests not only that there are free lunches, but that in some restaurants […] you can get paid to eat! To go from principle to practice, however, requires an act of faith that is not warranted by economic evidence and raises a number of important questions." [75]

The question therefore arose as to what level of energy efficiency should be considered optimal, with important implications for the size of the discrepancy with actual levels. Technology advocates had a tendency to see the widespread adoption of the best available technologies as the optimum, implying a large gap with actual levels, attributable to under-investment in energy efficiency. In contrast, market advocates had a tendency to interpret actual levels as resulting from perfect market equilibrium, implying virtually no gap but simply revealing a lack of consideration for the full costs of the measures. While the former view implies strong support for policy intervention, the other is skeptical about it.

These opposite views spurred research investigating the gap between actual and optimal energy efficiency levels in the early 1980s. This effort was initiated by Jerry A. Hausman [76], who estimated implicit discount rates as a proxy for the investment gap. As energy efficiency investments reduce future energy expenditure, the implied discount rate—the one that brings the net present value of investment to zero—reflects the value the investor associates with it. Using market data on room air conditioners of varying energy efficiency, Hausman found that the discount rates that rationalized observed purchase decisions were significantly higher than the market interest rate, which is the usual benchmark for privately optimal investment. This pattern was then confirmed with many other energy efficiency technologies [77].

The investigation was taken one step further in the early 1990s by Stanford University's Energy Modeling Forum (EMF). This framework gathered researchers from different backgrounds to sort out the different causes of the energy efficiency gap. The panel included three affiliates with economics departments (Adam B. Jaffe, Robert N. Stavins, Gilbert

[5] For a more recent account, see Lovins [74].

E. Metcalf), five affiliates with engineering, science and technology departments (Richard B. Howarth, Hillard G. Huntington, Blake E. Johnson, Willett Kempton, Linda L. Layne), one affiliate with a sociology department (Loren Lutzenhiser), five members of the Lawrence Berkeley National Laboratory (Jonathan G. Koomey, Mark D. Levine, Alan H. Sanstad, Lee Schipper, Richard Sonnenblick)—a prominent institution at the intersection of engineering and policy, one policy-maker from the U.S. EPA (Joel D. Scheraga) and one affiliate with the NERA consultancy company (Albert L. Nichols). Their collective effort resulted in the publication of a special issue of twelve papers on the energy efficiency gap in *Energy Policy* in 1994 (vol. 22 (10)).

Among the twelve papers collected in the special issue, Jaffe and Stavins [78]'s has had the most enduring impact. The paper built on a public economics framework—inherently microeconomic—to elicit simple conditions under which public intervention is warranted to promote energy efficiency.[6] Their main contribution was to make a distinction between market *barriers* and market *failures*. As normal components of well-functioning markets, market barriers prevent the best available technologies from being extensively adopted, but do not require policy intervention. This includes risk and heterogeneity in consumer preferences. In contrast, market failures occur when at least one of the assumptions of well-functioning markets according to mainstream economics (perfect competition, symmetric information, well-defined property rights) is violated. When this occurs, both energy efficiency and economic efficiency levels are suboptimal, thus calling for a policy fix.

Following this trend, the debate was narrowed down in the late 1990s to assessing whether the observed gaps should be interpreted as resulting from a market barrier or a market failure. A fringe represented by Roland J. Sutherland [82] in the United States and Franz Wirl [83] in Europe argued that most problems were in fact due to market barriers and that market failures, if any, were too costly to correct once policy-induced costs were taken into account. This stance remained marginal, however, as empirical evidence added up of the significance of market failures [58,72,84,85]. This became even clearer at the turn of the 21st century, when the energy-use externalities at the source of anthropogenic global warming were recognized as "the biggest market failure the world has seen" [86]. Still, techno-economic studies pointing to significant cost-saving opportunities, such as McKinsey & Co. [87]'s widely publicized one, were considered overly optimistic about energy efficiency.

The history sketched in this section highlights that the turn into the modern age of energy efficiency economics here again embraced more general economic concepts. Inspired by public economics, energy efficiency economists developed an overarching framework that accommodated a technological optimum alongside an economic one, thus favoring an interdisciplinary dialogue. While energy efficiency was studied through a macroeconomic lens in the classical age, the framework that emerged during the modern age was intrinsically microeconomic. This trend was paralleled by a shift of the focus from production to consumption, and policy intervention increasingly targeting households in a context of mass consumption.

3. The contemporary age (since the 2000s)

The energy efficiency gap remained by the late 1990s to be theoretically consolidated and empirically tested. The pursuit of this agenda induced two inter-related shifts in the economic analysis of energy efficiency, which together changed the status of energy efficiency from a niche issue into a more widespread one [88].

From a theoretical perspective, the focus on market failures was soon criticized for casting shadow on behavioral and institutional processes [12,71]. After all, high implicit discount rates could also be interpreted as reflecting departures from the perfect-rationality assumption. In parallel, the field of behavioral economics was gaining traction, to the point of becoming mainstream in economics [89], as illustrated by the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel (hereafter "Economics Nobel Prize") awarded to Herbert Simon in 1979, Daniel Kahneman in 2002 and Richard Thaler in 2017. Broadly speaking, behavioral economics is concerned with so-called internalities, or gaps between the utility people foresee upon making a decision (i.e. *ex ante*, or decision, utility) and the utility enjoyed when experiencing the consequences of that decision (i.e. *ex post*, or experienced, utility). To address internalities, Richard Thaler and Cass Sunstein [90] have proposed a new kind of policy intervention called *nudge*, meant to help people better align their choices with their own will.[7] The emergence of behavioral economics has deep implications for both theoretical and empirical economics, since challenging the foundations of theoretical microeconomics indeed requires a significant effort in empirical testing.

Energy efficiency soon proved a much-favored setting for seeking evidence of internalities and experimenting with nudges. The most commonly studied internalities in relation to energy efficiency have included context-dependent preferences—e.g. people replacing their windows to emulate their neighbor who did it—and inconsistent time preferences delaying investment decisions [85,88,93]. As for nudges, energy efficiency-related experiments mainly consisted in giving people information as to how their energy consumption compares with that of relevant others (usually their neighbors) (for a review, see [94]). These experiments were then deployed on a broader scale, allowing energy efficiency-focused papers to be published in the most exclusive economic journals (e.g. [95]).

Interestingly, here we can observe a move in the long-run relationship between the subfield of energy efficiency and the general trends of the economics discipline. While in the classical and modern age, energy efficiency specialists placed their reflections in the context of broader ideas (resource depletion, institutionalism, public economics), it has been the opposite in the contemporary age, as energy efficiency appeared to be a relevant case study to apply and test new economic frameworks (behavioral economics).

The shift of energy efficiency economics to behavioral economics has also been part of a broader trend in economics in which empirical studies came to prevail over theoretical ones. After decades of increasing sophistication, microeconomic theory had indeed reached a point in the late 1990s where the same model could make opposite predictions. Against this background, the economics community set out to test existing predictions rather than make new ones. The march towards the "credibility revolution" [96] produced important technical developments, such as reduced-form identification techniques based on randomized control trials and instrumental variables [97]. This movement too was celebrated by several "Economics Nobel Prize," awarded to Abhijit Banerjee, Esther Duflo and Michael Kremer in 2019 and Joshua Angrist and Guido Imbens in 2021.

Here again, energy efficiency proved a fruitful avenue for application. The highly sophisticated energy efficiency gap framework was based on welfare predictions, which are intrinsically difficult to test—for instance, discount rate estimates need to be compared to a theoretical benchmark that is somewhat arbitrary. The energy efficiency economics community therefore focused on a narrower manifestation of the energy efficiency gap—the *energy performance gap*, that is, the discrepancy between predicted and realized savings. By only requiring readily

[6] Public economics has gone through several stages since the Second World War. The immediate post-War period mostly focused on public-good issues [79,80]. The later period started in the 1980s and recommended public intervention to be minimal [81]. Jaffe and Stavins' approach is related to the latter.

[7] Nudges have been criticized both in relation to their effectiveness and to libertarian paternalism, in that they impose social norms without being legally binding [91,92].

available engineering predictions as the benchmark, the energy performance gap can easily be tested with reduced-form empirical techniques. Early studies had suggested that the gap was large with home energy retrofits, which produced very little effective savings [98–100]. With the new opportunities created by the credibility revolution, the issue gained renewed interest, culminating with the publication of an important field study in the *Quarterly Journal of Economics*, the most cited journal in the economic profession.[8] In this study based on a randomized control trial involving 30,000 households in Michigan, Meredith Fowlie et al. [102] found no profitable savings from home energy retrofits. They provided very little explanation for the phenomenon, except that it was plausibly not due to a rebound effect. This provides a striking illustration of the new state of the art in economics, more concerned with credible identification than with understanding the underlying process. The evidence of a large energy performance gap echoed insights from earlier studies using similar techniques [103–105]. To this day, the only cause that has been decently investigated is the issue of quality defects in home energy retrofits due to information asymmetries [106,107].

Overall, the robust—but narrow—finding that energy efficiency programs save little energy on average has renewed support for the skeptical view on energy efficiency in mainstream economics. This view, however, remains at odds with that of a range of energy analyses finding more sanguine results about the materiality of energy savings. This includes some large-sample studies (e.g. [108]), whole-cohort assessments (e.g. [109,110]) and aggregate studies (e.g. [111,112]).[9] The key difference between the two approaches is that the most recent empirical economic analyses place more emphasis on internal validity—in particular, establishing the causality of the processes under scrutiny—whereas energy analyses place more emphasis on external validity—the extent to which the results broadly apply. The resulting gap is yet another illustration of the growing divide between micro and macro perspectives on energy efficiency. These conflicting views are somewhat reflected in the mixed performance of energy efficiency policy, which, despite being massively and unambiguously advocated by major bodies [113], is subject to a persistent investment gap—the International Energy Agency [114] estimating that global investment in energy efficiency needs to triple by 2030 to be consistent with a path towards net zero emissions by 2050.

4. Opening up the energy efficiency gap framework

In 2004, at the fall of the modern age, Jaffe, Newell and Stavins [20] produced a diagram summarizing the state of the art of the debates inherent in the economics of energy efficiency. First sketched in Jaffe and Stavins's contribution to the 1994 special issue of *Energy Policy*—still the most cited article on energy efficiency across a wide range of disciplines (1800 citations, Google Scholar)—and then refined over the years, the diagram became a landmark when its final version was published in Jaffe, Newell and Stavins's entry on "energy efficiency" in Cutler J. Cleveland's 2004 *Encyclopedia of Energy*.

The diagram has two dimensions: energy efficiency on the vertical axis, economic efficiency on the horizontal one (Fig. 2a). From a baseline situation, overcoming market barriers (e.g. risk, heterogeneity of consumer preferences) is described as a move towards the upper left, increasing energy efficiency at the expense of economic efficiency. In contrast, correcting market failures (such as externalities, imperfect competition and asymmetric information) is described as a move towards the upper right, jointly improving energy and economic efficiency. The diagram considers market failures in the two relevant markets that underpin the production of energy services—energy markets and energy efficiency markets.

Our historical inquiry sheds a new light on Jaffe, Newell and Stavins's diagram. In recalling that the rebound effect—a re-optimization of energy consumption post-investment,[10] hence a market barrier—belongs in it, we point out that the diagram is not just a synthesis of the energy efficiency controversies of the modern age, but an overarching framework also accommodating older debates. Yet it does not seem any longer well-suited to the behavioral and empirical concerns that have characterized the contemporary era for two decades. On the one hand, the horizontal axis of the diagram, representing welfare, fails to accommodate the conceptual reflection about "behavioral welfare" [115]—how can welfare be assessed if decision-makers are not perfectly rational? On the other hand, the diagram is somewhat impractical for empirical analyses that take a reduced-form approach, not so much concerned with comparing an actual outcome with an optimal benchmark in welfare terms.[11] To further Jaffe, Newell and Stavins's ambition to build a synthetic framework of the economics of energy efficiency and make it fit for the 21st century, we propose two adjustments to the diagram.

First, we suggest to extend the scope of markets considered. Restricted to articulating energy and energy efficiency markets—the latter being understood as energy-consuming devices and equipment of varying performance—, the diagram should indeed include other markets crucially relevant for energy efficiency decisions. Home energy retrofit—a major yet complex energy efficiency measure—provides a bright illustration. As illustrated in Fig. 1, providing it often requires financial services (to cover the substantial upfront cost, typically in the several thousands to several tens of thousands of dollar range) and information services (audit needed to produce an energy performance certificate). Furthermore, it is closely connected to real estate markets. Lastly, in the case of rental housing, it also involves a differentiation between the investor (i.e. the landlord) and the energy user (i.e. the tenant). All of these accompanying markets (and associated so-called market failures) need to be considered alongside energy and product markets if one is to assess how a retrofit can be provided in the most efficient way. Broadening the scope of relevant markets in such a way can also be a first step towards reconciling micro- and macro-perspectives on energy efficiency.

While the proposed extension helps consider a broader set of so-called market failures, it still ignores the alleged behavioral anomalies that have been receiving so much attention in the contemporary age. Our second recommendation is therefore to introduce a new plane in Jaffe, Newell and Stavins' original framework to articulate decision and experienced utility. In this enhanced framework, depicted in Fig. 2b, the reference case devoid of behavioral anomalies (i.e. Jaffe, Newell and Stavins' original framework) corresponds to the 45-degree line. Along this line, decision and experienced utility coincide, meaning that agents experience no gap between the utility they expected before investment and that which they enjoy after investment. Outside this scope, economic agents are subject to a dissonance between the two—the aforementioned internalities. The internality is negative if experience turns out less beneficial than initially envisioned and positive otherwise. The latter case is essentially speculative, however, for in practice, most internalities tend to be negative (e.g. over-optimism, lack of self-control).

This enhanced framework reflects the broadening of the scope that occurred over the ages. The classical age set the stage by raising the issue that economic efficiency and energy efficiency were not necessarily aligned. The modern age further disentangled the economic problems that increase the divide between the two axes—market barriers—and

[8] The achievement is all the more significant that this outlet was recently criticized for not including a single article addressing the major issue of climate change [101].

[9] We thank an anonymous referee for bringing these references to our attention.

[10] This is one of the reasons why energy demand has consistently been found to be inelastic [57].

[11] The only work we are aware of using the diagram in such a reduced-form approach is [106].

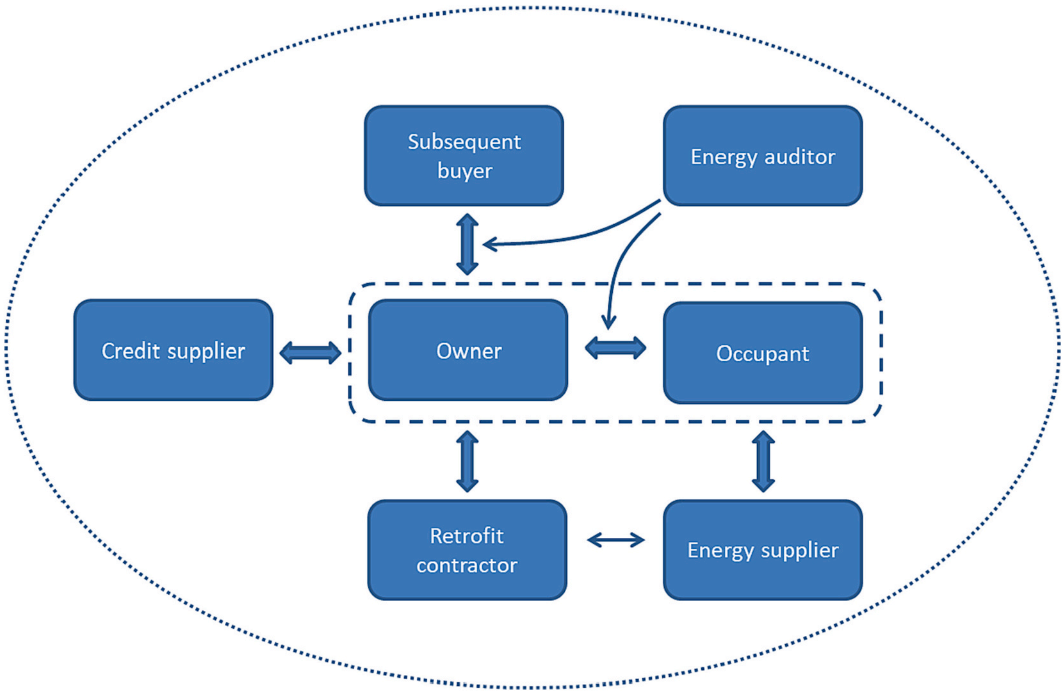

Fig. 1. The relevant agents and markets in the provision of home energy retrofits (enhanced from [116]).

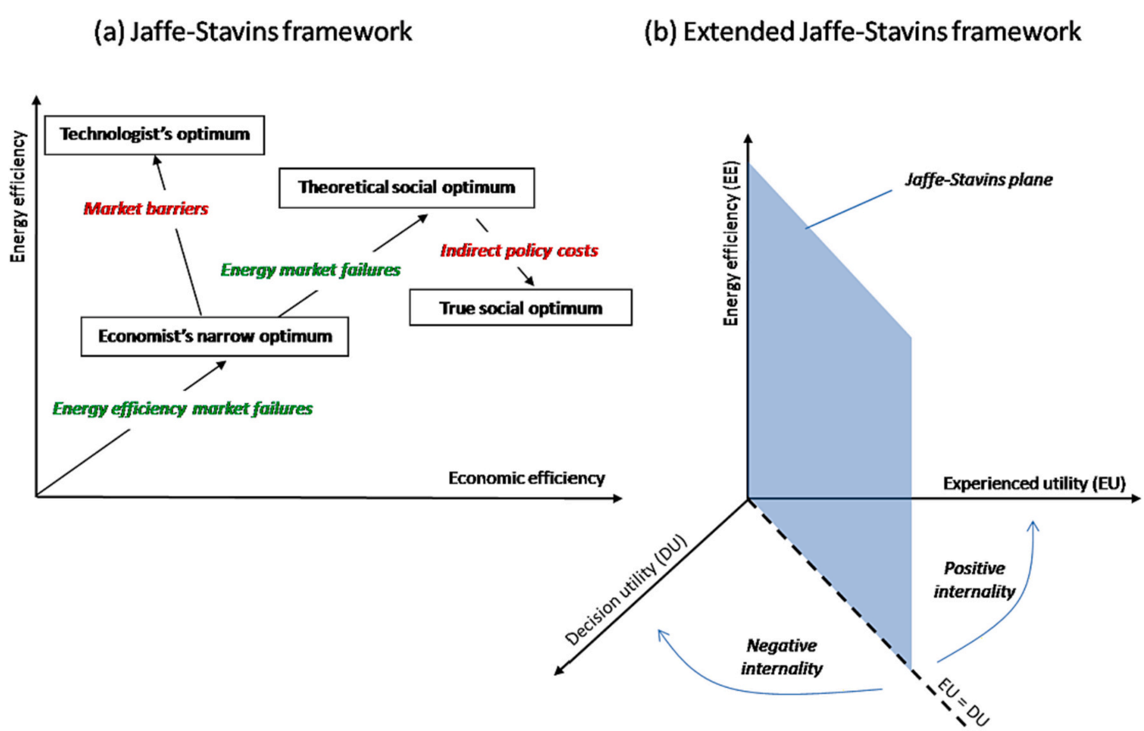

Fig. 2. Jaffe & Stavins' (1994) original diagram and our proposed extension.

those that narrow it—market failures. Lastly, the contemporary age has shed light on the limitations of simply considering two axes and the need for a third, behavioral one. The enhanced framework now makes it possible to visualize how individual and collective well-being vary under various policy interventions, in particular when nudges—meant to better align decision and experienced utility—interact with traditional remedies to market failure (energy taxes, energy efficiency subsidies, etc.).

5. Conclusion

Over the past century and a half, the economic interpretation of energy efficiency has changed in important ways, from a technological curiosity during the classical age to a typical case for thinking about market failures during the modern age to a practical field of experimentation with the most advanced behavioral and empirical techniques during the contemporary age. Our review of this long history has led us to identify regularities and important breakpoints.

The first regularity is that the evolution of the economics of energy efficiency has espoused that of the general economics discipline. In the classical age, the emergence of American institutionalism in the 1910s–1920s paved the way for an empirical, policy-oriented investigation of the rebound effect. In the modern age, the conceptual categories of 1980s–1990s public economics provided a microeconomic framework for conceptualizing the energy efficiency gap. Finally, the most recent contemporary age is strongly driven by the most recent developments in mainstream economics.

It should come as no surprise that field studies embrace more general developments in the discipline. Yet in the case of energy efficiency, our view is that the intertwining has been particularly strong.

The second regularity is that the conceptual shifts that we detected, from the rebound effect to the implementation of nudges, were systematically prompted by emerging societal concerns in relation to resource management: the depletion of exhaustible resources in the classical age, high oil prices in the modern age, and climate change in the contemporary age.

Finally, we found that changing economic perspectives on energy efficiency have not allowed the key controversies about the effectiveness of energy savings and the size of the rebound effect to be resolved. As a result, despite a generally broad support for energy efficiency, some rather skeptical views persist, which the mixed performance of energy efficiency policies has not managed to dissipate.

Against these regularities, the first important breakpoint in the evolution of the economics of energy efficiency is the reversal of the driver of change. While in the classical and modern ages, energy efficiency was mostly studied by borrowing from general economics, it has been the other way around in the contemporary age, with generalist economists leaning towards energy efficiency, seen as adequate case study for testing new economic concepts. This recent trend has allowed energy efficiency to feature in major economic journals while perhaps also making it more removed from advances in other disciplines [117]. As a result, the interdisciplinary dialogue that was central for instance to Stanford's Energy Modeling Forum, gathering engineers, economists and policy-makers, seems less important than it once was.

The second breakpoint is a shift from macro-oriented debates in the classical age towards a more micro-oriented framing, through public economics in the modern age and behavioral economics in the contemporary ages. What mattered for Jevons, Tryon and other figures from the classical age were the macroeconomic consequences of energy (in)efficiency in terms of industrialization, resource exhaustion and (de) coupling from economic growth. In the modern and contemporary ages, the attention shifted towards microeconomic (ir)rational behaviors, investment decisions and public incentives. This shift is all the more concerning that resource scarcity and climate change are far from being micro-only issues, spilling over macroeconomics.

Throughout our journey, we have identified Jaffe, Newell and Stavins' energy efficiency gap framework as a cornerstone synthesizing a wide range of issues raised across the classical and modern ages. To make it at the same time more operational, more up-to-date and still conceptually consistent, we have recommended two adjustments. First, we have suggested to extend the scope of the relevant markets to consider, a pre-requisite for reconciling micro and macro views. Second, we have recommended to enhance it with a behavioral dimension to take into account the most recent advances at the intersection of economics and psychology.

The future of the economics of energy efficiency is, obviously, hard to predict. Innovative methods in data science are increasingly pervasive in economics, and energy studies in particular [118]. In improving quantitative assessment, these methods can help overcome persistent difficulties, such as in the estimation of the size of rebound effects. This trend would however confirm the primacy of empirical research, at odds with our historical account that the economics of energy efficiency has always been a blend of empirical questions and theoretical propositions. The conceptualization of energy efficiency in economics is not yet complete, and we hope our extension of the Jaffe-Newell-Stavins diagram will help nourish it.

To go further, we should insist on the fact that energy efficiency is so ubiquitous in daily activity and economic behavior that it is certainly too big to be left to economics alone. The economics of energy efficiency would thus benefit from looking more closely at other disciplines, at other social sciences among those mentioned above in the introduction, in order to broaden its sources of inspiration and not appear to be a simple subsidiary of the developments of the general discipline of economics, or to be seen through a microeconomic lens only. This is a fascinating challenge for the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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