CIRED Working Paper
N° 2019-74 - Septembre 2019

The economics of energy efficiency, a historical perspective

Louis-Gaëtan Giraudet (ENPC, CIRED)[1]
Antoine Missemer (CNRS, CIRED)[2]

Contact : [1]giraudet@centre-cired.fr
[2]missemer@centre-cired.fr

Centre international de recherche sur l'environnement et le développement
Unité mixte de recherche CNRS - ENPC - Cirad - EHESS - AgroParisTech
Site web: www.centre-cired.fr Twitter: @cired8568
Jardin Tropical de Paris -- 45bis, avenue de la Belle Gabrielle 94736 Nogent-sur-Marne Cedex

Sept. 30, 2019 | v.2.1

Abstract:

Energy efficiency can be considered as a central pillar of global warming mitigation, with important co-benefits, including productivity gains, resource conservation or national security. It is also a subject of controversy between engineers and economists, who have divergent conceptions of the notion of optimality that delineates energy efficiency potentials. Modern surveys hardly go back beyond the 1970s and do not fully explore the reasons and conditions for the persistent differences between economists' and engineers' views. This paper provides such a historical account, investigating the positioning of economic analysis in contrast to the technical expertise on key energy efficiency topics – the rebound effect, the energy efficiency gap, and green nudges, from the 19th century to the present day. It highlights the permanence and evolution in the relationship that economists have had with technical expertise. An extension of the current conceptual framework is finally provided to connect our historical findings with avenues for future research.

Keywords: energy efficiency, market barriers and failures, engineering, nudge, history of economic thought

JEL Codes: B1, B2, L9, O3, Q4

Introduction

Energy efficiency can be considered as a central pillar of global warming mitigation, with important co-benefits, including productivity gains, resource conservation and a lower dependence on foreign energy sources. The notion of energy efficiency is intrinsically linked to that of energy service, *i.e.*, "those functions performed using energy which are means to obtain or facilitate desired end services or states" (Fell 2017). As general-purpose technologies (Bresnahan and Trajtenberg 1995), energy services are diffuse, ubiquitous across all sectors of the economy. Against this background, energy efficiency is defined as a technology minimizing the quantity of energy input (e.g., kWh, MJ, etc.) required to produce a given level of energy service (e.g., lumen, temperature, passenger.km, etc.). This technological notion has an economic meaning once one considers the cost of energy and seeks to attach economic value to energy services. Though primarily studied in the building (insulation, appliances) and transportation sector, energy efficiency infuses nearly all human activities, at both the microeconomic level of households and businesses and the macroeconomic considerations of resource management and environmental externalities.

This multiplicity of scales and fields of application implies a multiplicity of stakeholders: R&D offices, entrepreneurs, small and large companies, households, public authorities, energy utilities, etc. These stakeholders offer their specific expertise to identify and quantify energy efficiency potentials. These expertises can be complementary (e.g., R&D offices and companies need to work together to identify technologies that are not only feasible, but also profitable in the marketplace), but also competing. This is particularly the case for the engineering perspective on vs. the economic view of energy efficiency potentials. While engineering-based studies regularly emphasize important potentials for efficiency gains (e.g., McKinsey & Co. 2009), economists have long questioned these works by noting that if such potentials did exist, economic agents would spontaneously exploit them.[1]

These contrasted views translate into a "bottom-up" vs. "top-down" dichotomy in assessment models (Sorrell 2004a; W. J. Hausman and Neufeld 2006; Gerarden, Newell, and

[1] An illustration of the engineering stance, making economists sceptical, can be found in (Fickett, Gellings, and Lovins 1990, 7), when they famously write that energy efficiency potentials are "not a free lunch; it is a lunch you are paid to eat".

Stavins 2017), or between "technologist" vs. "economic" approaches (Huntington, Schipper, and Sanstad 1994; Sorrell 2004a; 2004b). This points to more general controversies about the relationship between engineering and economics. Already examined in the context of technological change (Rosenberg 1975), these controversies are now an emerging area of research in the field of history of economic thought (Duarte and Giraud 2018).

As for energy efficiency, although they mention the opposition, existing reviews do not fully explore the reasons and conditions for the persistent contrast between economic and technical views. Nor do they offer a long perspective on the history of these controversies, going back at best to the 1970s – and those who mobilize recent history focus primarily on policies and programmes, rather than on the ideas surrounding them (Rosenfeld 1999; Gibbons and Gwin 2004). A thorough historical investigation, in line with Turnbull (2017), is likely to uncover older episodes, where economists already built discourses on energy efficiency that were different from that of engineers. It can also help detect the permanence and evolution of the positioning of economic analysis in contrast to the technical expertise on energy efficiency, in order to identify obstacles and opportunities for deeper cooperation between researchers and practitioners in the future.

This paper provides such a historical account, through three controversial subjects across the last two centuries – the rebound-effect for the 1860s-1930s, the energy efficiency gap for the 1980s-1990s, and green nudges for the most recent period. The rebound effect refers to situations where energy savings are less than proportional to efficiency gains. The energy efficiency gap refers to suboptimal investment in energy efficiency, compared to a normative reference to be specified. Green nudges refer to policy intervention encouraging conservation in both the recipient's and society's interest. In each case, we show how economists have built an expertise different from that of engineers. We conclude that most recent developments related to behavioural approaches are likely to reconcile both camps, albeit shifting controversies to new demarcation lines.

Section 1 focuses on the rebound effect, from the 1860s to the 1930s, starting with Jevons's well-known intuition in *The Coal Question* (1865), which was already the result of a different positioning, founded on market mechanisms, from that of engineers. We also show that the rebound effect remained an important topic in the economic literature at least until the 1930s. Section 2 explores the controversies over the energy efficiency gap, which started in the 1980s and culminated in the mid-1990s. Economists' discourse on energy efficiency became more sophisticated, embedding it within a broader decision framework to distinguish themselves from engineers. Section 3 shows how the reinforcement of behavioural perspectives in the field of energy economics opened up a third-way capable of reconciling economists and engineers around the idea of *behavioural barriers*, but displacing controversies towards the effectiveness and legitimacy of *green nudges*. Section 4 proposes a synthetic framework to summarize our historical findings, and to take stock of the future prospects in the economics of energy efficiency. The final section is for concluding remarks.

1. The rebound effect (1860s-1930s)

The rebound effect, defined above as energy savings that are less than proportional to energy efficiency improvements, can take three major forms (Linares and Labandeira 2010): the direct rebound effect, which consists of less-than-proportional savings in the use of the very service that was subject to efficiency improvements; the indirect rebound effect, coming from the income effect created by the savings, leading to an increased consumption of other energy services; and the general-equilibrium rebound effect, resulting from changes in relative prices that stimulate energy-intensive sectors.[2] In addition to this typology, an important question is the magnitude of the rebound, which can be very different from one situation to another. It can simply consist of savings slightly smaller than efficiency gains, but it can also produce a somewhat counter-intuitive situation, in which energy consumption actually *increases* – generally referred to as backfire effect.

From a theoretical perspective, the rebound effect can be easily conceived and explained: in the production process, efficiency gains are translated into cost reductions, and price mechanisms adjust to a new equilibrium in which savings are lower than in standard expectations. Empirical evidence of rebound effects is less obvious, as it is regularly argued in the literature (Sorrell 2009; Linares and Labandeira 2010). They are context-dependent and do not always cover the whole typology mentioned above: Herring

[2] Greening et al. (2000) add a fourth category of rebound, yet the distinction between direct and indirect effects remains central to their categorization.

(2006) reports that the direct rebound effect usually remains quite small (20%), while the indirect and general-equilibrium forms face methodological challenges that prevent them from being thoroughly measured. These methodological limitations should nonetheless not undermine the importance of rebound mechanisms in many sectors in which unitary improvements scarcely result in significant savings, such as home heating and vehicle fuel consumption.

The modern understanding of the rebound effect dates back to the late 1970s and early 1980s, when Len Brookes (1979) and Daniel Khazzoom (1980) emphasized the low impact of efficiency programmes because of savings clearly less than proportional to energy efficiency improvements. The contemporary literature acknowledges Brookes's and Khazzoom's pioneering inspiration (Alcott 2008; Sorrell 2009). It is well know, however, that the very origin of the conceptualization of the rebound effect is to be found in the ancient writings of W. Stanley Jevons, in his 1865 (2nd ed. 1866) book *The Coal Question* (Robine 1990; Alcott 2005; 2008; Sorrell 2009; Missemer 2012; Turnbull 2017).[3] After collecting data on coal consumption over decades, confronting them to major innovations in the efficiency of steam engines, Jevons concludes:

> "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth."
> (W. S. Jevons 1866, 123)

Interestingly, he not only mentions the direct rebound effect, but also indirect forms, as soon as economic sectors are interrelated:

> "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."
> (W. S. Jevons 1866, 136)

Although the rebound effect only constitutes a small part of Jevons's argument on coal depletion – the book covers a wider range of issues (Missemer 2012), it remains a key-

[3] Sieferle (2001) reports that Sedgwick would have provided a preliminary version of the rebound mechanism before Jevons. Alcott (2008) reviews the economic writings before Jevons sketching rebound effects, but for goods and services outside the energy sector.

argument in peripheral, less-known contributions produced after *The Coal Question*, in the late 1860s. On January 16, 1867, at Carpenters' Hall in Manchester, Jevons explained:

> "Some people say we shall […] economise our coal, use it more carefully, and get more power out of it in the steam engine. The fact is, we are doing that now. Iron is now made by much less coal than it used to be, yet we use more coal than ever. […] The fact is that coal is a thing of such value to us that we cannot help spending it – there is more temptation than we can resist. It is such a useful substance that we find wealth in it more and more every year." (W. S. Jevons 1867, 26)

A similar statement was formulated at the Royal Institution, on March 13, 1868:

> "Economy, it may be pointed out, does not tend to reduce the industrial consumption of coal, but acts in the opposite direction: by increasing the profitableness of coal-labour, it extends its use. Almost every improvement in the engine for the last century and a half has been directed to economizing the consumption of coal; and yet the use of the engine and the quantities of coal consumed advanced *pari passu* with its economical performance." (W. S. Jevons 1868, 31)

Jevons wrote this in a context surrounded by intense debates on the future of British coal reserves (White 1991a; 1991b; Madureira 2012; Mathis 2018; Albritton Jonsson 2019). He was particularly influenced by William Armstrong's warning address at the 1863 Newcastle conference of the British Association for the Advancement of Science (White 2004). Sieferle (2001) reports that many engineers and geologists, from the late 18th century, had formulated estimations about the future of British coal reserves. Most of them considered that there was enough fuel for several centuries. Jevons provided a contrasted view, by forecasting an exponential increase of fuel demand putting rapid pressure on cheap-coal reserves. One reason for this view was the presence of rebound mechanisms in his estimates, turning any efficiency improvement into a poison rather than a remedy.

Retrospectively, Jevons's argument and pessimistic scenario can be interpreted as a move in the coal-depletion debate meant to distinguish himself from other parties (Missemer 2017, chp.1; 2018). While many observers considered technical progress and fuel efficiency gains as promising ways to reduce coal consumption (Alcott 2008, 7–8), Jevons used the rebound mechanism to envision a completely different future. In other words, the rebound effect led Jevons to propose an economic discourse on coal depletion emancipated from engineers' view, usually enthusiastic about the opportunities created by technology. Jevons's innovation mainly consisted in including demand and price mechanisms, so far neglected by engineers, into the energy-sector dynamics.

The debate between economic views and engineering views over the impact of technical improvements in the coal sector continued in the late 19th century. In 1878, Anthony J. Mundella gave a talk at the Statistical Society, expressing his trust in the capacity of engineering to circumvent exhaustion issues. Jevons, and a few other participants in the meeting, in turn expressed their scepticism on the matter. In the same year, John Marshall (1878, 325–28), professor at Yorkshire College, reformulated the opposition between economists and engineers on fuel efficiency, explaining that the economic rationale is rarely directed towards savings.[4] In France, economist Yves Guyot (1881, 90–91) confirmed the position of his corporation, noting that despite major improvements in fuel efficiency, production processes use considerably more fuel than before. In the 1890s, in the US, some engineers such as the former president of the American Institute of Mining Engineers, John Birkinbine, still refused to take into account the economic expertise – and rebound mechanisms – in their fuel forecasts (Kent 1895, 324), which is a sign of persistent disagreements.

Studies mentioning Jevons's pioneering research on fuel efficiency rarely show any interest in these little known subsequent episodes, just as they rarely mention the role of the rebound effect in debates between economists and engineers in the early 20th century. A historical inquiry however provides insightful results on the matter. In 1915, Hebert S. Jevons, W. Stanley's son, wrote an extensive book on the *British Coal Trade*. In his essay, he depicted many aspects of fuel activity, including the role of technical improvements (Missemer 2015; Turnbull 2017). Referring to his father's book, he explained that the energy efficiency gains of the late 19th century did not permit a reduction of coal consumption, even per capita (H. S. Jevons 1915, 746–47). He put forward an alternative explanation rooted in the existence of the rebound effect. H. S. Jevons's book has not left a strong mark on the history of economics, but it was recognized as an important contribution at the time, as Alfred Marshall's mention in *Industry and Trade* (1923, 586f) reveals.

[4] J. Marshall was one of the first to call for empirical tests of the rebound effect.

In the US, the early 20th century was the time of the First Conservation Movement, under T. Roosevelt's administration. In politics, this meant an increasing role assigned to experts and engineers in the design of public policies, including environmental and resource management. Gifford Pinchot's doctrine was to merge technical efficiency and political regulation to promote a sound use of natural resources for present and future generations (Pinchot 1910). When economists such as Lewis C. Gray (1913; 1914) and Richard T. Ely (1918) came to participate in conservation debates and provide economic principles underlying the new doctrine (Smith 1982; Crabbé 1983; Gorostiza 2003; Missemer 2017; Turnbull 2017), they were confronted to the question of technological improvements for fuel efficiency. Engineers still considered that conservation was primarily a matter of engineering (Drinker 1919, 30). In contrast, while establishing his optimal extraction principles, Gray (1913) shed light on the role of demand and the need for regulating it as much as supply. Even if he did not refer to the rebound effect, he thus highlighted the role, neglected by engineers, of demand and prices in the fuel sector, in the lineage of Jevons.

The energy debates that took place in the US in the 1920s confirmed both the persistent controversies between engineers and economists, and the permanence of the rebound-effect argument, half a century after *The Coal Question*. It was then finally agreed that engineers and economists should work together to elaborate sound resource management programmes (Hammar 1931). In the late 1920s, the Brookings Institution launched a research project on the role of energy in economic development, involving both engineers and economists (Missemer and Nadaud 2019). The participants in this project suggested that the field of mineral economics should be defined as the intersection between economics, geology and engineering (Moulton 1932; Tryon and Berquist 1932). Yet working together does not necessarily imply sharing the same views and values. Within the Brookings project, engineers and economists joined forces in the writing of a common book, *Mineral Economics* (Tryon and Eckel 1932), but through separate contributions (Pogue 1933). While engineers focused on particular sectors (copper, petroleum, etc.), economists tried to provide more general pictures (e.g., Tryon 1927; Tryon and Rogers 1930; Tryon and Berquist 1932). Doing so, they notably focused their attention on fuel efficiency. The Great War was the occasion of important efforts on the matter (Tryon and Rogers 1930, 358), but in the same way that past unitary gains resulted in global increases in consumption, the last improvements are certainly promised to lead to what we now call less-than-proportional savings (Tryon and Rogers 1930, 361). This reference to the rebound effect is not a coincidence; it directly comes from Jevons's old research. Tryon and Rogers cite *The Coal Question* on several occasions (1930, 363f, 364f) – which is not the case for engineering contributors to the Brookings project, and they especially quote Jevons for the rebound effect in its backfire version:

> "The ultimate effect of the advance in efficiency may be to increase the consumption of fuel. As Jevons pointed out in 1865, "As a rule, new modes of economy will lead to an increase of consumption, according to a principle recognized in many parallel instances [...]"." (Tryon and Rogers 1930, 364f)

This episode shows that the history of the rebound effect is not just the reigniting of Jevons's pioneering contribution by Brookes and Khazzoom in the late 1970s and early 1980s. From Jevons to the first decades of the 20th century, the rebound effect was discussed, commented and regularly emphasized to characterize the economic discourse on fuel efficiency in contrast to the engineering optimism towards technological improvement.

Every time in this early history, what was at stake was an underestimation of demand and price mechanisms in engineers' views, and a clear reaction against it by economists. The focus of engineers on the supply side was not specific to energy issues. Knowles (1952) has shown that the same could be observed for other markets, such as for labour: most of the time, engineers built relevant estimates for producers' reactions to shocks or public regulations, but they neglected market mechanisms, in particular demand feedback. When it came to technology, they appeared more optimistic than economists about substitution and efficiency mechanisms – the long-term dynamics of the economy can seem to prove them right – but for the short and medium term, their partial view of market mechanisms caused estimation errors, or disappointment regarding the effectiveness of incentives. On the contrary, by insisting on market mechanisms, economists such as W. S. Jevons, Y. Guyot, H. S. Jevons, F. G. Tryon and H. O. Rogers built a contrasted discourse on energy efficiency.

Interestingly, this historical demarcation line was also the one chosen by Len Brookes in the late 1970s to constitute an autonomous economic expertise on energy efficiency. His 1979 contribution was in fact a book review of a bottom-up, engineering contribution (Leach et al. 1979) reporting the insufficient results of the energy efficiency programmes conducted in the 1970s in the UK. With the rebound effect, Brookes thus positioned the economic analysis of fuel efficiency at odds with the engineering expertise, in the same way as Jevons and his other predecessors.

In the late 20th century, the economics of energy efficiency was the heir to this long history of differentiation towards engineering, through the consideration of market mechanisms, in particular the role of demand and prices. With the increasing complexity of energy issues in the broader context of sustainable development, new controversies over fuel efficiency appeared between engineers and economists, creating new demarcations lines.

2. The energy efficiency gap (1980s-1990s)

The concept of energy efficiency gap developed in the late 1970s and 1980s and reached maturity in the early 1990s. Broadly speaking, the energy efficiency gap refers to the notion that investment in energy efficiency is, *by some measure*, suboptimal. The problem can equally affect the extensive and intensive margins of investment; that is, produce *too few* and/or *too small* investments. The crux of the concept is that the reference taken for optimality differs in engineers' and economists' views, with important consequences for any conclusion as to the magnitude of the gap. As we will see below, the concept creates a new demarcation line between engineers and economists which superimposes on, and to some extent even encompasses, the one associated with the rebound effect.

The reflection about the optimal level of energy efficiency was initiated in the United States by the first assessments of the energy efficiency policies implemented in response to the oil crisis of the 1970s. So-called Demand-side management (DSM) programmes were rolled out between 1975 and 1978 in many States. In a context of growing concerns about dependence on foreign energy sources, local pollution associated with coal-powered electricity generation plants and nuclear risk, DSM programmes were meant to leverage the knowledge electric and gas utilities have of energy end-uses in order to reap the social benefits of energy savings. Practically, DSM gave rise to a number of programmes involving subsidies, information provision, etc., at the local level. In the first economic assessment of these programmes, Joskow and Marron (1992) pointed to a 'negawatt-hour cost' – the cost of saving one unit of energy – substantially higher than that suggested by engineers. Led at the time by Amory Lovins from the Rocky Mountain Institute, the community of engineers was referred to by economists as one of 'efficiency advocates.' Joskow and Marron based their estimates on data self-reported by electric utilities. They attributed the discrepancy to a number of issues, including failure to account for all relevant costs, reliance on projections rather than actual measurement of savings, and failure to account for non-additional participants in subsidy programmes, often referred to as 'free riders.' This seminal contribution ignited a methodological dispute that continues to this day.[5]

While Joskow and Marron's evaluation was the first to address the multiple programmes that a utility would rollout within its overarching DSM policy, the economic evaluation of individual programmes had started earlier on and identified two phenomenon – abnormally high implicit discount rates and a gap between predicted and realized energy savings.[6] From an economic perspective, implicit discount rates are those that rationalize observed investment choices. They are estimated as the unknown variable that equates the net present value of investment to zero. An implicit discount rate is deemed abnormal if it exceeds conventional values, usually aligned with the returns households can enjoy in financial markets – typically 5-7%. A 'normal' discount rate is a notion of optimality that appeals to both engineers and economists. While it postulates a model of choice, it is the smallest common denominator in that regard that speaks to both engineers and economists. Moreover, it is not too demanding in terms of data requirements, as it can be assessed for each individual choice, without relying on some elasticity estimated at the market level. Hausman (1979) was the first to provide evidence of abnormally high implicit discount rates in relation to energy efficiency investment. The research effort inspired many others, which would soon be reviewed by Train (1985). The other phenomenon –

[5] The most recent developments include Loughran and Kulick (2004), Auffhammer, Blumstein, and Fowlie (2008) and Arimura et al. (2012).

[6] From a methodological perspective, narratives of underinvestment collected in surveys formed a third type of evidence (e.g., Blumstein et al. 1980). These are however less systematic and thus not examined here.

lower-than-predicted, or missing, energy savings – was a prefiguration of the finding Joskow and Marron reached at a more systematic scale. Though the problem was first noted by Hirst and Goeltz (1985), it was not until Metcalf and Hassett (1999) that it became widely recognized. Interestingly, it has recently attracted renewed interest with the publication by Fowlie, Greenstone and Wolfram (2018) of a study finding virtually no savings in a heavily-subsidized weatherization programme.[7] Compared to abnormal discount rates, the identification of missing savings does not rely on any preconception of a model of choice. Still, engineering predictions embed normative assumptions that are not always clearly elicited.

Both abnormal discount rates and missing savings can be seen as manifestations of a gap between reality and some notion of optimality – respectively conventional market returns and engineering projections. The identification of these gaps raised a number of questions, including: What problems are at the source of these gaps? Are they economically important? If so, should they be addressed by policy intervention? These were the starting point of the elaboration of a conceptual framework known as the 'energy efficiency gap' and meant to list, characterize and assess the significance of various sources of the gap. This reflection was the result of a collective effort coordinated by the Energy Modeling Forum (EMF) in the early 1990s. Convened by Stanford University, the EMF gathers an interdisciplinary community interested in energy modelling and involving both economists and engineers. The reflection resulted in the publication in 1994 of a special issue in *Energy Policy* on the energy efficiency gap. We find here many analogies with the 1932 book *Mineral Economics* published as part of the Brookings programme and mentioned above. Although the integration of engineering and economic perspectives was certainly more advanced in the EMF than it was at the Brookings Institution, the special issue in *Energy Policy* featured the same segmentation as in *Mineral Economics*, with separate papers for each view.

[7] To put these contributions in perspective, the citation count of these references in the Web of Science if 8 for Hirst and Goeltz (1985), 84 for Metcalf and Hassett (1999) and 12 for Fowlie, Greenstone and Wolfram (2018), as of August 23, 2019. Fowlie, Greenstone and Wolfram's study is the most cited among a broader set of references reaching the same finding, including Davis, Fuchs and Gertler (2014), Graff Zivin and Novan (2016) and Giraudet, Bourgeois and Quirion (2018).

Among the papers in the issue, that of Jaffe and Stavins (1994c) turned out to be the most impactful. By proposing an original conceptual framework, it laid down a whole new research agenda. The most essential feature of the framework was a distinction between market barriers and market failures. Market barriers are considered as normal components of markets (e.g., risk, heterogeneity in consumer preferences). In contrast, market failures occur when the basic assumptions of well-functioning markets – perfect competition, perfect information and well-defined property rights – are violated. While both may prevent adoption of energy efficiency technologies from being widespread, only the latter justify policy intervention. Borrowed from public economics, this dichotomy provides a framework to think about conflicts between engineering and economist views. In essence, while market failures might be a concern for both economists and engineers, market barriers only worry the latter. In this regard, the rebound effect can be seen as a market barrier: a pure economic mechanism that nevertheless prevents maximization of energy savings. Likewise, the problems pointed out by Joskow and Marron (1992) – who personify the economist stance – are essentially market barriers, which lead the authors to seriously question the economic rationale for DSM programmes. One can see in the success of Jaffe and Stavins' paper a victory of the economist view taken by the authors.[8] This however casts shadow on the fact that the framework developed in the special issue was remarkably consensual, in particular by being validated by contributions from several researchers from the Berkeley Lab (Alan Sanstad, Richard Howarth), a prominent institution in the field of integrated energy-economy modelling. In contrast, somewhat extreme economist views developed in parallel without gaining significant traction (Sutherland 1996; Wirl 1997).

The 'energy efficiency gap' was both a framework to think of the engineer vs. economist dichotomy and, perhaps more importantly, a research programme. Much effort remained to be done to give it substance by identifying, characterizing, and quantifying the problem. For instance, a problem frequently pointed out in relation to energy efficiency is credit constraints. How important is it? Is it simply a market barrier – after all, economic decisions are all about maximizing outcomes under credit constraints – or is there

[8] The authors made their point in several references, including in *Energy Policy* (Jaffe and Stavins 1994c), *Resource and Energy Economics* (Jaffe and Stavins 1994b) and the *Energy Journal* (Jaffe and Stavins 1994a). They kept refining their diagram until the definitive version was published in the *Encyclopedia of Energy* (Jaffe, Newell, and Stavins 2004), with Richard Newell as a co-author.

something more specific to it (e.g., information asymmetries) in the context of energy efficiency that makes it a market failure? To a large extent, the energy efficiency gap research programme was not followed up by serious investigation. This changed in the early 2000s, when concerns over anthropogenic global warming gained prominence. Carbon dioxide externalities associated with energy use were recognized as the greatest market failure humanity had ever faced (Stern 2006). Attention was drawn to energy efficiency by engineering studies portraying it as the most cost-effective way of reducing carbon dioxide emissions. In the most impactful of these studies, McKinsey & Co (2009) suggested that most energy efficiency technologies were socially profitable not only for modest values of the social cost of carbon – indicating that they should be prioritized to reduce emissions – but also for *negative* values – indicating that they should be prioritized *anyway*. While the first argument remained uncontroversial, economists objected to the second that if it were true, energy efficiency would be everywhere, which was not the case. This was clearly a reminiscence of the by now old debate between economists and engineers, only occurring in a new context.[9]

Altogether, the state of the art of the economics of energy efficiency had settled as follows by the 2000s: market barriers were deemed significant, and it was considered the engineers' duty to improve their projections; market failures were also deemed important, but chiefly in energy market, e.g., energy-use externalities; in contrast, market failures in energy efficiency markets, if anything, remain to be elicited. This was summarized in important reviews, including Sorrell (2004b), Gillingham, Newell and Palmer (2009) and Linares and Labandeira (2010). Importantly, we saw the energy efficiency gap was a broader conceptual framework than the rebound effect in that the former encompassed the latter and deployed the same fault lines in a more systematic way. We will see now that an even broader framework is now developing, building on somewhat new divides.

[9] It was also a reminiscence of the notions of 'no-regret potential' for, and co-benefits of, carbon dioxide emission reductions, which both gained popularity in the IPCC community.

3. Green nudges (since 2000s)

The energy efficiency gap essentially is a neo-classical economic concept, in the sense that, by drawing a line between market failures and non-market failures, it provides a framework to think of energy efficiency investment in situations where the fundamental assumptions of well-functioning markets – perfect competition, perfect information and well-defined property rights – are violated. The framework also has a practical appeal in that it provides clear guidance for policy-making: for any market failure proved significant, there is a policy remedy to implement.

Evidence is growing, however, that energy efficiency decisions are subject to new economic problems which the energy efficiency gap framework is not well-suited to accommodate: behavioural anomalies. Behavioural anomalies occur when perfect rationality, the essential assumption of the neo-classical economic framework, is violated. These include context-dependent preferences, inconsistencies in time and risk preferences, and the use of heuristics in lieu of proper optimization.[10] To put it simply, behavioural anomalies result in people making mistakes in the sense that they make decisions that do not satisfy them *ex post*. Put still another way, they create a gap between decision, or *ex ante* utility and experienced, or *ex post* utility. Economic research into irrationality and behavioural anomalies reached full recognition with the Nobel Prizes awarded to Herbert Simon in 1978, Daniel Kahneman in 2002 and Richard Thaler in 2017. What has come to be known as behavioural economics is now part of most standard frameworks in economic analysis.[11] Unlike with market failures, the policy implications of behavioural anomalies are ambiguous. Whenever there is a market failure, some agent in the economy benefits from a rent – competitive, informational, legal – at the expense of another agent; in this context, it has been uncontroversial that the Government should intervene to level the playing field. In contrast, intervening to address behavioural anomalies would be equivalent for the Government to helping people reconcile with themselves. This kind of intervention, coined ‘nudge’ by Thaler and Sustein (2008) in their eponymous best-seller, is more controversial.

[10] Before the 2000s, behavioural anomalies were sometimes tackled in the energy efficiency literature through the concepts of behavioural obstacles or bias (e.g., Eyre 1997). However, they were neither central nor empirically tested at the time.

[11] On the disputed integration of behavioural economics into neoclassical economics, see Angner (2019).

If someone is having issues figuring out her decision utility, how can the Government do better without somehow substituting its own norms for that person's? Nudges are indeed akin to 'libertarian paternalism' in that they impose social norms without being legally binding (Salvat 2014; Schubert 2017).

Throughout the emergence of behavioural economics, energy demand has proved a highly favoured setting for seeking evidence of irrational behaviour and experimenting with nudges. In particular, feedback experiments in which people are given information as to how their energy consumption compares to that of relevant others (usually their neighbours) were set up early (for a review, see Fischer 2008). These have been more recently deployed on much a broader scale, which improved the statistical power and credibility of the approach, allowing some researchers to publish in major economic journals (e.g., Allcott and Rogers 2014). In such experimental settings, average behaviour can be seen as a social norm which people seek to conform to. Accordingly, energy users are found to adjust their consumption by regressing to the mean, even when their consumption is below average. This is not the case if additional structure is imposed on social norms, for instance by adding smileys to consumption feedback. Then, consumers using less energy than average receive positive smileys, to which they respond by keeping their consumption low; meanwhile, those using more than average receive negative smileys and reduce their consumption. Albeit seen as a successful nudge – low-cost, highly effective – harnessing context-dependent preferences, feedback interventions illustrate an important issue, namely the intricacies between behavioural anomalies and the market barriers and failures that define the energy efficiency gap. In particular, electricity billing is typically not given in real time, nor is it detailed for specific usages. In other words, the price people pay for different energy services typically is incomplete information. One can therefore expect people to respond in a suboptimal way to energy bills, even if they do not include feedback. This pre-existing distortion is important to take into account when one seeks to assess the impact of feedback interventions.

Taking stock, behavioural economics adds a new fault line between decision and experienced utility that is found to be highly relevant to energy efficiency decisions. This new fault line is a form of reconciliation between engineers and economists. Economists now start to recognize the point made by engineers that people do not behave rationally. As a result, behavioural economics now concentrates most of the research effort that is put in energy efficiency. This focus however leaves aside important blind spots, in particular in the way behavioural anomalies interact with both the market barriers and market failures making up the energy efficiency gap.

4. A synthetic framework

Our historical journey has revealed demarcation lines between engineers and economists that first emerged in the context of energy efficiency through the rebound effect. In the late 20th century, divergences on the role of market feedbacks were supplemented by contrasted views of decision-making mechanisms. Most recently, the acknowledgement of behavioural barriers has been an opportunity to reconcile the economic and the engineering perspectives over energy efficiency. Both camps consider these barriers as central, legitimizing policy measures for energy improvements. Yet behavioural analysis led to a new fault line – one between nudge advocates and a more sceptical community – about the effectiveness of nudges, which might be strongly driven by pre-existing market failures. Not only does this new fault line not clearly separate out economists and engineers – there are advocates of both positions in both camps – it does not either fit into the conceptual framework that prevailed up to now; indeed, it is seemingly orthogonal to the usual demarcation lines structuring the debate over the energy efficiency gap.

Against this background, we propose a revised version of the Jaffe-Stavins (1994c) and Jaffe-Newell-Stavins (2004) diagram, extended to accommodate behavioural anomalies (Figure 1). Because behavioural analysis brings a new dimension to our understanding of energy efficiency, the diagram is in 3D, distinguishing a space 'decision utility' (DU) and a space 'experienced utility' (EU). This diagram is more complex than the original one, reflecting the enriched analytical framework currently at stake in the economics of energy efficiency. It is both the result of our historical investigation, which has shown the increasing widening of the debate, and a starting-point to help identify the areas of discussion over barriers and failures to be addressed in the design of energy efficiency policies.

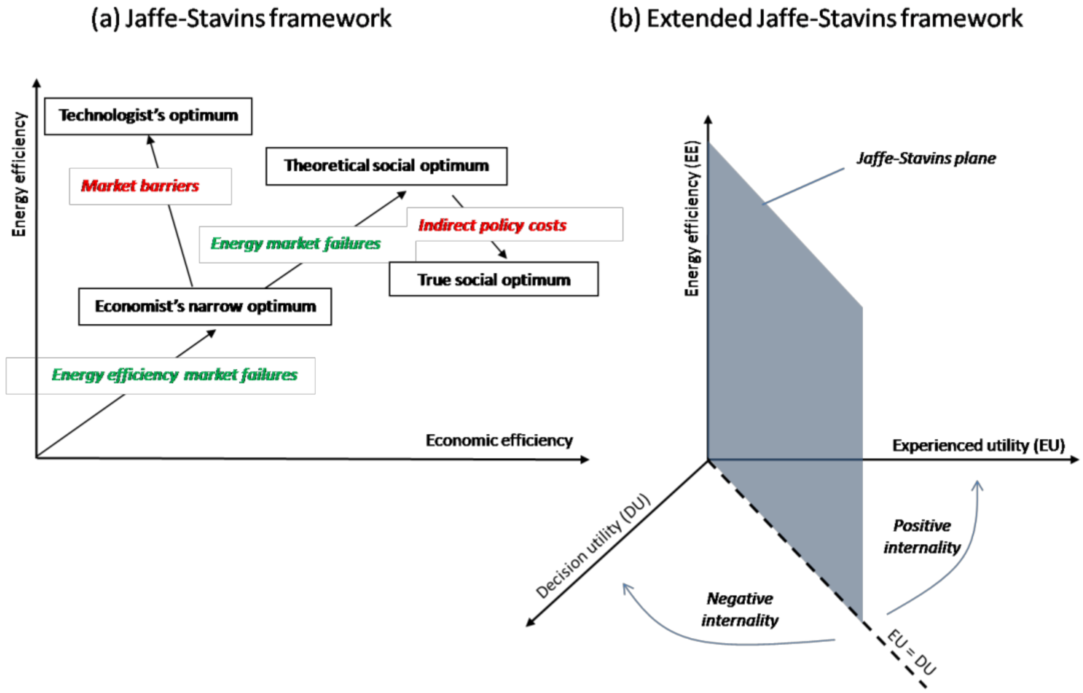

Figure 1: Jaffe & Stavins' (1994) original diagram and its proposed extension

Conclusion

Investigating the history of the economics of energy efficiency is a new challenge both from a contemporary perspective – existing reviews scarcely go back beyond the 1970s – and from a history-of-economic-thought perspective – this little-studied subject provides a bright illustration of the controversies between economists and engineers throughout history. We have researched the permanencies and evolutions of the relationships between economics and engineering on the subject of energy efficiency, and have obtained the following results.

First, the origins of the controversies are not limited to W. S. Jevons's ancient intuition on the rebound effect. Market mechanisms and demand feedbacks had been arguments used by economists for several decades, at least until the 1930s, to build up expertise distinct from that of engineers. This means that already at the time, disagreements were difficult to overcome and when joint research programmes were carried out (e.g., at the Brookings Institution), the different participants had difficulty understanding each other and working together.

Second, the long history of the economics of energy efficiency is one of iterative diversification and redefinition of the demarcation lines between economists and engineers. After the divergences on market mechanisms, the debates over the energy efficiency gap gave birth to new disagreements, on the decision-making of agents and on the distinction between *barriers* and *failures*. The 1990s reconfigured controversies, to the point of integrating the rebound effect into the discussion on the energy efficiency gap. Research cooperation between engineers and economists continued to pose difficulties, in similar ways to what we had highlighted for the 1920s.

Third, the acknowledgement of behavioural barriers to optimal investment in energy efficiency offered an opportunity for the reconciliation of economists and engineers. It seems however that a new fault line appeared, between those accepting *green nudges* and those more sceptical about their legitimacy, both in ethical and economic terms. Interestingly, this new dividing line does not separate economists from engineers, but more heterogeneous constellations of researchers and experts. This could be a historically unprecedented reconfiguration, made possible by behavioural approaches.

To synthetize these findings and to make the link between our historical inquiry and future research in the economics of energy efficiency, we proposed an update of the famous Jaffe-Newell-Stavins diagram, showing the orthogonal character of the behavioural perspective with respect to the historical oppositions in the field. This makes it possible to highlight research avenues for the future, by pointing out the areas where we need further work to articulate market and behavioural mechanisms, and distinguish barriers from failures, to design legitimate policy measures.

* * *

References

Albritton Jonsson, Fredrik. 2019. 'The Coal Question before Jevons'. *Historical Journal* in press.

Alcott, Blake. 2005. 'Jevons' Paradox'. *Ecological Economics* 54 (1): 9–21.

———. 2008. 'Historical Overview of the Jevons Paradox in the Literature'. In *The Myth of Resource Efficiency. The Jevons Paradox*, edited by John M. Polimeni, K. Mayumi, Mario Giampietro, and Blake Alcott, 7–78. Oxon & New York: Earthscan from Routledge.

Allcott, Hunt, and Todd Rogers. 2014. 'The Short-Run and Long-Run Effects of Behavioral Interventions: Experimental Evidence from Energy Conservation'. *American Economic Review* 104 (10): 3003–3037.

Angner, Erik. 2019. 'We're All Behavioral Economists Now'. *Journal of Economic Methodology* 26 (3): 195–207. https://doi.org/10.1080/1350178X.2019.1625210.

Arimura, Toshihide, Shanjun Li, Richard G. Newell, and Karen Palmery. 2012. 'Cost-Effectiveness of Electricity Energy Efficiency Programs'. *Energy Journal* 33 (2): 63–99.

Auffhammer, Maximilian, Carl Blumstein, and Meredith Fowlie. 2008. 'Demand Side Management and Energy Efficiency Revisited'. *Energy Journal* 29 (3): 91–104.

Blumstein, Carl, Betsy Krieg, Lee Schipper, and Carl York. 1980. 'Overcoming Social and Institutional Barriers to Energy Conservation'. *Energy* 5 (4): 355–371. https://doi.org/10.1016/0360-5442(80)90036-5.

Bresnahan, Timothy F., and Manuel Trajtenberg. 1995. 'General Purpose Technologies "Engines of Growth"?' *Journal of Econometrics* 65 (1): 83–108. https://doi.org/10.1016/0304-4076(94)01598-T.

Brookes, Len. 1979. 'A Low Energy Strategy for the UK by G. Leach et al.: A Review and Reply'. *Atom* 269: 3–8.

Crabbé, Philippe J. 1983. 'The Contribution of L. C. Gray to the Economic Theory of Exhaustible Natural Resources and Its Roots in the History of Economic Thought'. *Journal of Environmental Economics and Management* 10 (3): 195–220.

Davis, Lucas W., Alan Fuchs, and Paul Gertler. 2014. 'Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico'. *American Economic Journal: Economic Policy* 6 (4): 207–238.

Drinker, Henry Sturgis. 1919. 'The Need of Conservation of Our Vital Natural Resources as

Emphasized by the Lessons of the War'. *Science* 49 (1254): 27–31.

Duarte, Pedro Garcia, and Yann Giraud. 2018. 'Economics and Engineering: Institutions, Practices and Cultures'. Duke.

Ely, Richard T. 1918. 'Conservation and Economic Theory'. In *The Foundations of National Prosperity. Studies in the Conservation of Permanent National Resources*, edited by Richard T. Ely, Ralph H. Hess, Charles K. Leith, and Thomas Nixon Carver, 1–92. New York: Macmillan.

Eyre, Nick. 1997. 'Barriers to Energy Efficiency: More Than Just Market Failure'. *Energy & Environment* 8 (1): 25–43. https://doi.org/10.1177/0958305X9700800103.

Fell, Michael James. 2017. 'Energy Services: A Conceptual Review'. *Energy Research & Social Science* 27: 129–140.

Fickett, Arnold P., Clark W. Gellings, and Amory B. Lovins. 1990. 'Efficient Use of Electricity'. *Scientific American* 263 (3): 64–75.

Fischer, Corinna. 2008. 'Feedback on Household Electricity Consumption: A Tool for Saving Energy?' *Energy Efficiency* 1 (1): 79–104.

Fowlie, Meredith, Michael Greenstone, and Catherine Wolfram. 2018. 'Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program'. *Quarterly Journal of Economics* 133 (3): 1597–1644.

Gerarden, Todd D., Richard G. Newell, and Robert N. Stavins. 2017. 'Assessing the Energy-Efficiency Gap'. *Journal of Economic Literature* 55 (4): 1486–1525.

Gibbons, John H., and Holly L. Gwin. 2004. 'Conservation Measures for Energy, History Of'. In *Encyclopedia of Energy*, edited by Cutler J. Cleveland, 1:649–659. Amsterdam: Elsevier Science. https://www.sciencedirect.com/science/article/pii/B012176480X000346.

Gillingham, Kenneth, Richard G. Newell, and Karen Palmer. 2009. 'Energy Efficiency Economics and Policy'. *Annual Review of Resource Economics* 1: 597–620.

Giraudet, Louis-Gaëtan, Cyril Bourgeois, and Philippe Quirion. 2018. 'Long-Term Efficiency and Distributional Impacts of Energy Saving Policies in the French Residential Sector'. Paris.

Gorostiza, Jose Luis Ramos. 2003. 'Ethics and Economics: From the Conservation Problem to the Sustainability Debate'. *History of Economic Ideas* 11 (2): 31–52.

Graff Zivin, Joshua, and Kevin Novan. 2016. 'Upgrading Efficiency and Behavior: Electricity Savings from Residential Weatherization Programs'. *Energy Journal* 37 (4): 1–23.

Gray, Lewis C. 1913. 'The Economic Possibilities of Conservation'. *Quarterly Journal of Economics* 27 (3): 497–519.

———. 1914. 'Rent under the Assumption of Exhaustibility'. *Quarterly Journal of Economics* 28 (3): 466–489.

Guyot, Yves. 1881. *La Science Économique*. Paris: C. Reinwald, Bibliothèque des sciences contemporaines.

Hammar, Conrad H. 1931. 'Economic Aspects of Conservation'. *Journal of Land & Public Utility Economics* 7 (3): 282–290.

Hausman, Jerry A. 1979. 'Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables'. *Bell Journal of Economics* 10 (1): 33–54.

Hausman, William J., and John L. Neufeld. 2006. 'Engineers and Economists: Historical Perspectives on the Pricing of Electricity'. *Technology and Culture* 30 (1): 83–104. https://doi.org/10.2307/3105432.

Herring, Horace. 2006. 'Energy Efficiency - A Critical View'. *Energy* 31: 10–20. https://doi.org/10.1016/j.energy.2004.04.055.

Hirst, Eric, and Richard Goeltz. 1985. 'Estimating Energy Savings Due to Conservation Programmes: The BPA Residential Weatherization Pilot Programme'. *Energy Economics* 7 (1): 20–28.

Huntington, Hillard G., Lee Schipper, and Alan H. Sanstad. 1994. 'Editors' Introduction'. *Energy Policy* 22 (10): 795–797.

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins. 2004. 'Economics of Energy Efficiency'. In *Encyclopedia of Energy*, edited by Cutler J. Cleveland, 2:79–90. Amsterdam: Elsevier Science. https://doi.org/10.1016/b0-12-176480-x/00228-x.

Jaffe, Adam B., and Robert N. Stavins. 1994a. 'Energy-Efficiency Investments and Public Policy'. *Energy Journal* 15 (2): 43–65.

———. 1994b. 'The Energy Paradox and the Diffusion of Conservation Technology'. *Resource and Energy Economics* 16 (2): 91–122.

———. 1994c. 'The Energy-Efficiency Gap. What Does It Mean?' *Energy Policy* 22 (10): 804–810. https://doi.org/10.1016/0301-4215(94)90138-4.

Jevons, Herbert Stanley. 1915. *The British Coal Trade*. London: London and Norwich Press.

Jevons, William Stanley. 1865. *The Coal Question. An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines*. London: Macmillan.

———. 1866. *The Coal Question. An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines*. 2nd ed. London: Macmillan.

———. 1867. 'On Coal'. In *Papers and Correspondence of William Stanley Jevons, Vol.7*, edited by R.D. Collison Black, 18–28. London: Macmillan.

———. 1868. 'On the Probable Exhaustion of Our Coal Mines'. In *Papers and Correspondence of William Stanley Jevons, Vol.7*, edited by R.D. Collison Black, 28–35. London: Macmillan.

Joskow, Paul L., and Donald B. Marron. 1992. 'What Does a Negawatt Really Cost? Evidence from Utility Conservation Programs'. *Energy Journal* 13 (4): 41–74. https://doi.org/10.5547/issn0195-6574-ej-vol13-no4-3.khawaja.

Kent, William. 1895. 'The Relation of Engineering to Economics. Address before Section D of the AAAS'. *Science* 2 (37): 321–334.

Khazzoom, Daniel. 1980. 'Economic Implications of Mandated Efficiency in Standards for Household Appliances'. *Energy Journal* 1 (4): 21–40.

Knowles, William H. 1952. 'Economics of Industrial Engineering'. *ILR Review* 5 (2): 209–220.

Leach, Gerald, Christopher Lewis, Frederic Romig, A. Van Buren, and G. Foley. 1979. *A Low Energy Strategy for the United Kingdom*. London: International Institute for Environment and Development.

Linares, Pedro, and Xavier Labandeira. 2010. 'Energy Efficiency: Economics and Policy'. *Journal of Economic Surveys* 24 (3): 573–592. https://doi.org/10.1111/j.1467-6419.2009.00609.x.

Loughran, David S., and Jonathan Kulick. 2004. 'Demand-Side Management and Energy Efficiency in the United States'. *Energy Journal* 25 (1): 19–43.

Madureira, Nuno Luis. 2012. 'The Anxiety of Abundance: William Stanley Jevons and Coal Scarcity in the Nineteenth Century'. *Environment and History* 18 (3): 395–421.

Marshall, Alfred. 1923. *Industry and Trade*. 4th ed. London: Macmillan.

Marshall, John. 1878. 'The Coal Question. Continued'. In *Coal: Its History and Uses*, edited by Thomas E. Thorpe, 320–350. London: Macmillan.

Mathis, Charles-François. 2018. 'King Coal Rules: Accepting or Refusing Coal Dependency in Victorian Britain'. *Revue Française de Civilisation Britannique* XXIII (3).

McKinsey & Co. 2009. ‘Unlocking Energy Efficiency in the U.S. Economy’. Milton: McKinsey Global Energy and Materials.

Metcalf, Gilbert E., and Kevin A. Hassett. 1999. ‘Measuring the Energy Savings from Home Improvement Investments: Evidence from Monthly Billing Data’. *Review of Economics and Statistics* 81 (3): 516–528.

Missemer, Antoine. 2012. ‘William Stanley Jevons’ The Coal Question (1865), beyond the Rebound Effect’. *Ecological Economics* 82: 97–103.

———. 2015. ‘La Peur Du Déclin Économique Face à l’épuisement Des Ressources Naturelles, de W. Stanley Jevons à Herbert S. Jevons (1865-1915)’. *Revue Économique* 66 (5): 825–842.

———. 2017. *Les Économistes et La Fin Des Énergies Fossiles (1865-1931)*. Paris: Classiques Garnier.

———. 2018. ‘Fossil Fuels in Economic Theory - Back to the 19th Century British Debates’. *Revue Française de Civilisation Britannique* XXIII (3).

Missemer, Antoine, and Franck Nadaud. 2019. ‘Energy as a Factor of Production: Back to a Pioneering Research in the Institutionalist Context’. #BNREproject working-paper. Paris.

Moulton, Harold G. 1932. ‘Preface’. In *Mineral Economics. Lectures under the Auspices of the Brookings Institution*, edited by Frederick G. Tryon and Edwin C. Eckel, vii–viii. New York & London: McGraw-Hill.

Mundella, Anthony John. 1878. ‘What Are the Conditions on Which the Commercial and Manufacturing Supremacy of Great Britain Depend, and Is There Any Reason to Think They Have Been, or May Be, Endangered?’ *Journal of the Statistical Society of London* 41 (1): 87–134.

Pinchot, Gifford. 1910. *The Fight for Conservation*. New York: Doubleday, Page & Co.

Pogue, Joseph E. 1933. ‘Review of “Mineral Economics” by H. F. Bain and Others’. *Journal of Political Economy* 41 (4): 572–573.

Robine, Michel. 1990. ‘La Question Charbonnière de William Stanley Jevons’. *Revue Économique* 41 (2): 369–394.

Rosenberg, Nathan. 1975. ‘Problems in the Economist’s Conceptualization of Technological Innovation’. *History of Political Economy* 7 (4): 456–481.

Rosenfeld, Arthur H. 1999. ‘The Art of Energy Efficiency: Protecting the Environment with Better Technology’. *Annual Review Energy Environment* 24: 33–82.

Salvat, Christophe. 2014. 'Behavioral Paternalism'. *Revue de Philosophie Économique* 15 (2): 109. https://doi.org/10.3917/rpec.152.0109.

Schubert, Christian. 2017. 'Green Nudges: Do They Work? Are They Ethical?' *Ecological Economics* 132: 329–342. https://doi.org/10.1016/j.ecolecon.2016.11.009.

Sieferle, Rolf Peter. 2001. *The Subterranean Forest. Energy Systems and the Industrial Revolution*. Cambridge (UK): The White Horse Press.

Smith, Gerald Alonzo. 1982. 'Natural Resource Economic Theory of the First Conservation Movement (1895-1927)'. *History of Political Economy* 14 (4): 483–495.

Sorrell, Steve. 2004a. 'Introduction'. In *The Economics of Energy Efficiency. Barriers to Cost-Effective Investment*, edited by Steve Sorrell, Eoin O'Malley, Joachim Schleich, and Sue Scott, 1–23. Cheltenham & Northampton: Edward Elgar Publishing.

———. 2004b. 'Understanding Barriers to Energy Efficiency'. In *The Economics of Energy Efficiency. Barriers to Cost-Effective Investment*, edited by Steve Sorrell, Eoin O'Malley, Joachim Schleich, and Sue Scott, 25–93. Cheltenham & Northampton: Edward Elgar Publishing.

———. 2009. 'Jevons' Paradox Revisited: The Evidence for Backfire from Improved Energy Efficiency'. *Energy Policy* 37 (4): 1456–1469.

Stern, Nicholas. 2006. *The Economics of Climate Change. The Stern Review*. Cambridge (UK): Cambridge University Press.

Sutherland, Ronald J. 1996. 'The Economics of Energy Conservation Policy'. *Energy Policy* 24 (4): 361–370.

Thaler, Richard, and Cass Sunstein. 2008. *Nudge. Improving Decisions about Health, Wealth, and Happiness*. New Haven: Yale University Press.

Train, Kenneth. 1985. 'Discount Rates in Consumers' Energy-Related Decisions: A Review of the Literature'. *Energy* 10 (12): 1243–1253. https://doi.org/10.1016/0360-5442(85)90135-5.

Tryon, Frederick G. 1927. 'An Index of Consumption of Fuels and Water Power'. *Journal of the American Statistical Association* XXII (159): 271–282.

Tryon, Frederick G., and Frederick E. Berquist. 1932. 'Mineral Economics - An Outline of the Field'. In *Mineral Economics. Lectures under the Auspices of the Brookings Institution*, edited by Frederick G. Tryon and Edwin C. Eckel, 1–36. New York & London: McGraw-Hill.

Tryon, Frederick G., and Edwin C. Eckel, eds. 1932. *Mineral Economics. Lectures under the*

Auspices of the Brookings Institution. New York & London: McGraw-Hill.

Tryon, Frederick G., and H. O. Rogers. 1930. 'Statistical Studies of Progress in Fuel Efficiency'. In *Transactions Second World Power Conference (Berlin)*, edited by F. zur Nedden and C. T. Kromer, 343–365. Berlin: Vdi-Verlag Gmbh.

Turnbull, Thomas. 2017. 'From Paradox to Policy: The Problem of Energy Resource Conservation in Britain and America, 1865-1981'. PhD Thesis, University of Oxford.

White, Michael V. 1991a. 'Frightening the "Landed Fogies'': Parliamentary Politics and The Coal Question"'. *Utilitas* 3 (2): 289–302.

———. 1991b. 'Where Did Jevons' Energy Come From?' *History of Economics Review* 15: 60–72.

———. 2004. 'In the Lobby of the Energy Hotel: Jevons's Formulation of the Postclassical "Economic Problem"'. *History of Political Economy* 36 (2): 227–271.

Wirl, Franz. 1997. *The Economics of Conservation Programs*. Dordrecht: Kluwer Academic Publishers.