From the Coal Age to Carbon Democracy: The Co-Evolution of Energy Regimes and Economic Thought[a]

Da era do carvão à democracia do carbono: a coevolução dos regimes energéticos e do pensamento econômico

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Abstract: The study argues that the material and networked properties of energy carriers have co-evolved with the language of economics. It periodises the transformations from coal's debates on stocks and efficiency, through the grid logic of electricity, the oil era's regime of abundance and stability, and the post-1973 discourse of intensity and conservation, to the atmospheric budgeting of the carbon age. Methodologically, it combines close reading and comparative discourse analysis of disciplinary texts with cross-readings of administrative regulations, engineering reports, and public writing regimes. Through mini-cases on the United Kingdom, the United States, and Europe, it maps the shift of efficiency from the machine to system operation and rule design; of scarcity from underground to the atmosphere; of substitution from price signals to infrastructural embeddedness; and of externalities from the local to the global scale. The findings indicate that, under high uncertainty, quantity instruments (budgets/caps) outperform price-based approaches and that effective policy architectures require the sequencing of scale–distribution–allocation. The contribution is to reconstruct the theory–measurement–rule chain by bringing to light

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the bidirectional processes of translation and circulation between energy regimes and economic thought.

Keywords: Energy regimes. Carbon budget. Institutional design.

Resumo: O estudo defende que as propriedades materiais e de rede dos vetores energéticos evoluíram em paralelo com a linguagem da economia. Ele periodiza as transformações desde os debates sobre reservas e eficiência no contexto do carvão, passando pela lógica da rede elétrica, pelo regime de abundância e estabilidade da era do petróleo e pelo discurso pós-1973 sobre intensidade e conservação, até o orçamento atmosférico da era do carbono. Metodologicamente, combina a leitura minuciosa e a análise comparativa do discurso de textos disciplinares com leituras cruzadas de regulamentos administrativos, relatórios de engenharia e regimes de produção de textos públicos. Por meio de minicasos no Reino Unido, nos Estados Unidos e na Europa, o estudo mapeia a mudança da eficiência da operação de máquinas para a operação de sistemas e a concepção de regras; da escassez do subsolo para a atmosfera; da substituição dos sinais de preço para a integração em infraestruturas; e das externalidades da escala local para a global. Os resultados indicam que, em condições de alta incerteza, os instrumentos quantitativos (orçamentos/limites máximos) apresentam melhor desempenho do que as abordagens baseadas em preços e que arquiteturas de políticas eficazes exigem o sequenciamento de escala–distribuição–alocação. A contribuição consiste em reconstruir a cadeia teoria–medição–regra, trazendo à tona os processos bidirecionais de tradução e circulação entre regimes energéticos e o pensamento econômico.

Palavras-chave: Regimes energéticos. Orçamento de carbono. Estrutura institucional.

JEL: P28. Q50.

Introduction and Thesis: The Co-Evolution of Energy Regimes and the Language of Economics

This study is organized around the thesis that modern economics' key concepts—scarcity, efficiency, substitution, externalities, welfare, and the triad of "scale, distribution, and allocation"—have been shaped, in historically specific contexts, through processes of co-evolution with the material and institutional features of energy regimes. By "co-evolution," we mean, on the one hand, that the physical and networked properties of energy carriers—exemplified by coal, electricity, oil, and, today, carbon budgets—have contributed to reweighting the problem-priorities and conceptual vocabulary of economic analysis; and, on the other hand, that this language, articulated through narratives of efficiency and externalities, has fed back into energy-related regulation, investment, and social imaginaries, thereby producing new institutional forms. Accordingly, the text is neither merely a technical "history of energy technologies" nor solely a "history of ideas"; rather, it is a narrative of translation and circulation unfolding at their point of contact. Within this framework, the article traces, simultaneously, discursive continuities and ruptures stretching from coal's position in the British industrial era to the rhetoric of "rationality" and economies of scale associated with twentieth-century eletrification; from the oil age's abundance–security dualism to the language of efficiency and conservation forged in the energy crises of the 1970s; and finally to the price–quantity debates that have come to structure post-1990 climate/carbon regimes (Wrigley, 2010; Hughes, 1983; Fouquet, 2008; Smil, 2017; Graf; Steininger, 2019).

The Coal Question's warning that efficiency improvements might paradoxically increase energy use—an insight now widely referred to as the Jevons paradox or "rebound effect"—profoundly shaped nineteenth-century imaginaries of scarcity and substitution, and subsequently endowed the "conservation/efficiency–security of supply" nexus with distinctive ethical and political salience in later economic discourse. The problematisation Jevons established, when coupled in the early twentieth century with the electrification discourse's emphasis on the grid, load factor, and scale, made it possible for efficiency to be coded not merely as a technical attribute but as an administrative and institutional rationality as well. As energy regimes changed, so too did the substantive content of the concept and the contours of public reason (Jevons, 1865/1906; Hughes, 1983; Fouquet, 2008). In Jevons's own formulation, "the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth." This statement captures—at an early juncture—the idea that efficiency gains can expand demand through price and scale mechanisms, and therefore that it is not always possible to transcend the material limits of energy regimes simply through "saving" (Jevons, 1865).

In the oil age—especially during the 1945-1973 interval—norms of abundance, standardization, and price stability intersected with the economic lexicon through clusters of concepts such as "elasticity of substitution," "strategic reserves," and "supply diversification"; the shocks of 1973-1979, in turn, produced a rupture in this language by re-centering energy intensity, conservation, and demand management. Commission reports and textbooks from this period register an "invention moment" in which "energy economics" was effectively promoted from a technocratic specialty to an object of public policy and statecraft (Yergin, 1991; Graf; Steininger, 2019; Smil, 2017).

From the 1990s onward, in the context of climate change, (i) ecological economics' thermodynamic and scale-first emphasis and (ii) the "prices versus quantities" framework—concerned with instrument choice under uncertainty—have proceeded in the climate policy design literature as two lines that come into contact yet do not fully overlap. This point of contact renders visible, in some debate, a partial shift in the object of measurement from welfare/flow indicators toward a budget/stock logic; in others, it also shows the persistence of the agenda of internalizing externalities and measuring welfare. For this reason, we approach the transformation not as a single-axis displacement but as a process of layering that becomes especially pronounced within selected institutional domains (climate governance, carbon accounting, and policy design). This narrative also foregrounds the link between the materiality of energy carriers and politico-social organization. Carbon Democracy's thesis differentiates between coal's political effects rooted in organized labor power and the distinct power topologies associated with oil, structured through pipelines and maritime transport, and thus distinguishes the channels through which economic reason secures public legitimacy. Fossil Capital's reading of coal capitalism and Power to the People's account of energy transitions offer a comparative historical lens for making visible the extent to which narratives of productivity and growth are embedded in specific energy carriers (Mitchell, 2011; Malm, 2016; Kander *et al.*, 2014).

Economic thought's conceptual apparatus is not wholly external to energy regimes; rather, it is constituted, in specific contexts, in an isomorphic and co-structural relation with them. Nodal points such as efficiency and substitution in the coal age, rationality and scale in the era of electrification, abundance and security in the oil age, and—under carbon constraints—the increasing weight accorded to externalities and quantity-based instruments have taken shape alongside the technical and logistical properties of energy carriers and the institutional codifications of those properties. For this reason, making sense of the economic lexicon requires reconstructing the infrastructures of energy regimes, just as making sense of energy politics requires mapping the conceptual geography through which economic language renders those regimes intelligible and governable (Hughes, 1983; Smil, 2017; Daly, 1996; Weitzman, 1974).

The research questions make visible the thesis's bidirectional movement:

(1) Across the sequence from coal to electricity, from oil to carbon budgeting, which concepts are brought to the forefront of economic language by the physical properties of energy carriers—such as energy density, storability, transportability, and network economies—and by associated modes of governance, including monopolies, grids, and transnational regimes of security of supply?

(2) In the reverse direction, which institutional arrangements in the energy domain (rationing; taxation/Emissions Trading Systems (ETS); strategic reserves; standardization) and which narratives of legitimacy (an ethics of scarcity, a pedagogy of conservation, the notion of a "fair price," and security discourse) are produced by concepts crystallized within economic language?

(3) What are the comparative forms of this co-evolution? Between Britain's coal-and-grid legacy, the United States' oil-and-security regime, and continental Europe's experience with electrifi-

cation and planning, which shared vocabularies and which divergences can be traced?

Rather than econometric testing, the study combines close reading with methods from discourse analysis and conceptual/intellectual history. We read four types of material in tandem: (i) intra-disciplinary texts (Jevons, Hotelling, Weitzman; textbooks); (ii) administrative/technical documents (energy commissions, IEA/OECD reports, electrification plans); (iii) political-public texts (parliamentary debates, central bank/planning documents); and (iv) popular/visual culture (advertisements, posters, official albums). This multi-layered reading strategy aims to trace how the chain linking theory, measurement, and rule design is repeatedly reconfigured across successive energy regimes.

This text proposes a concept- and instrument-oriented historiographical reading that traces how concepts enter into circulation across different "writing regimes" and are re-signified, without being confined to the canonical author–work line that often structures the history of economic thought. To this end, we simultaneously follow: (i) shifts in the definitions of key concepts (scarcity, efficiency, substitution, externalities); (ii) the links these shifts establish with measurement techniques and policy instruments; and (iii) the functions through which the same concept is mobilized across different institutional sites (academia, bureaucracy, market regulators). This approach resonates with historiographic debates on how Georgescu-Roegen's bioeconomic legacy has been reconstructed within different "intellectual lineages": for instance, Missemer's analysis of modes of rereading within the degrowth literature and Allisson's toolkit for tracing "intellectual legacies" provide a methodological grounding for the tracking logic adopted here. Moreover, scholarship in the history of economic thought that examines the post-1950 diversification of environmental/ecological economic ideas (e.g., Berta, Debref; Vivien) clarifies the study's rationale: the aim is not to narrate a triumphal story of a single school, but to show which questions are prioritized within economic language—and which measurement–rule combinations are legitimized—as the materiality of energy carriers changes (Berta *et al.*, 2021; Missemer, 2017; Allisson, 2020).

For this reason, when claiming that expressions such as "planetary budget" and "carbon budget" have become visible not only in academic texts but also across a wider public–technical sphere of circulation, it is important to demonstrate this in a bounded way through concrete examples. For instance, in IPCC's AR6 reports, the concept of the "remaining carbon budget" is explicitly defined and its relation to temperature targets is visualized (IPCC, 2021; IPCC, 2023). At the level of central banks and supervisory authorities, the Network for Greening the Financial System climate-scenarios framework presents transition pathways as a quantified scenario set; its technical documentation makes clear that achieving targets is discussed against the background of a "limited carbon budget" (e.g., "persistently elevated levels of global emissions against the backdrop of a limited carbon budget…", NGFS, 2023, Technical Documentation – Phase IV). European Central Bank's climate risk stress test (2022) and the Bank of England's Climate Biennial Exploratory Scenario outputs (2022) can be read as applied instances translating this scenario logic into the domain of financial risk assessment. In the political–public arena, the United Kingdom's carbon budget delivery plans and the reports of the Climate Change Committee (CCC, 2020; CCC, 2025) render "the budget" a calculable object of rule. Taken together, these examples support the claim that the "budget/limit" language discussed in the text becomes visible within certain institutional literatures; by contrast, we deliberately refrain from asserting that the concept has become hegemonic across all writing regimes.

In natural resource economics, Harold Hotelling's model of exhaustible resources provided a powerful framework for construing scarcity as a discounted price path over time; in the climate-era debates, Martin Weitzman's "prices versus quantities" approach under uncertainty has offered an analytic foundation for the comparative design of instruments such as carbon taxes and Emissions Trading Systems (ETS). By contrast, Nicholas Georgescu-Roegen and Herman Daly's emphasis on "scale first, allocation second" has pushed economic reasoning to rethink the production-possibility frontier in light of physical constraints (thermal losses, entropy) and planetary budgets. Taken together, these debates make it possible to treat efficiency not merely as a technical ratio, but also as an institutional and ethical problematic (Hotelling, 1931; Weitzman, 1974; Daly, 1996; Ayres; Warr, 2009; Kümmel, 2011).

1. Conceptual Map

This section clarifies the article's conceptual scaffolding in two steps. First, it specifies the semantic core around which the concepts traced in the study—scarcity, efficiency, substitution, and externalities—are followed. It then shows how these concepts circulate and are reconfigured not only in academic texts but also in administrative/technical reports and regulatory writings concerned with rule design, thereby preventing the narrative from dispersing between a "history of ideas" and an "energy/economic history." For this reason, we treat the concepts not as fixed dictionary definitions but as "nodes of circulation" that are continually recontextualized in relation to the material and networked properties of energy carriers (density, transportability, storability, and grid-compatibility). Our claim of "co-evolution" is therefore deliberately qualified: energy regimes do not unilaterally "rewrite" the language of economics; rather, at certain historical ruptures they reweight the language's problem priorities by more tightly articulating specific concepts (scarcity, efficiency, substitution, externalities) with distinct objects of measurement and forms of rule (Hughes, 1983; Fouquet, 2008; Smil, 2017; Wrigley, 2010).

The analysis reads four "writing regimes" in conjunction:

(1) the canonical texts and argumentative nodes of economic thought (Jevons, Hotelling, Pigou/Coase, Weitzman, Daly; selected textbooks and debates)

(2) engineering/technology narratives on the history of energy systems and infrastructures (e.g., network economies, standardization, and the logic of natural monopoly)

(3) policy and administrative documents of "counting and rule-making" (commission reports, national plans, regulatory frameworks, carbon accounting/MRV)

(4) a limited set of texts that register the public circulation of concepts (parliamentary debates, institutional reports, and selected dossiers in the mainstream press). Our selection criterion is not representativeness but the capture of moments in which the "concept–measurement–rule" linkage is established; accordingly, for each period we conduct close readings of a small

> number of "key texts." This method is also consistent with scholarship in the history of economic thought that examines how Georgescu-Roegen's bioeconomic legacy and environmental/energy-oriented economic ideas have been reconstructed across different intellectual lineages (Allisson, 2020; Berta, Debref; Vivien, 2021; Missemer, 2017).

Scarcity (the displacement of the object): We trace scarcity not merely as the axiom of "unlimited wants–scarce resources," but through the question of which object of scarcity is being governed. In the coal age, scarcity is articulated not only in terms of the depletion of reserve stocks, but also through linking the pace of consumption and the intensity of dependence to national power (Jevons, 1865/1906). With electrification, scarcity becomes tied less to fuel itself than to the continuity of service flows (light/heat/power) and to the grid's operating capacity; in the oil age, scarcity discourse is organized primarily around geopolitical disruption and security of supply rather than physical exhaustion. In the climate era, the object shifts once again: what becomes "scarce" is no longer underground stocks but the atmosphere's capacity to absorb emissions—the remaining carbon budget. In the sections that follow, we track these displacements through the language of measurement deployed (reserves, flows, intensity, budgets) and the policy instruments attached to it (reserve regimes, demand management, diversification, and budget/cap mechanisms).

Efficiency (the social translation of a ratio): In the text, efficiency is traced not merely as an engineering ratio but as a "relation of consequences" embedded in economic reasoning. Jevons's rebound logic provides an early illustration that efficiency improvements do not automatically reduce aggregate consumption; yet we do not treat Jevons as the single "origin" of twentieth-century energy economics, but rather as a threshold text in the translation of the efficiency–scale relation into public reason. In the electrification era, efficiency expands from the machine–fuel dyad to a rationality of grid operation (load curves, standardization, scale); with the crises of the 1970s, the concepts of energy intensity and demand-side management connect the language of efficiency to administrative targets. In the climate era, efficiency becomes a component of rule design considered alongside regulatory instruments such as carbon pricing, standards, and quotas; hence the question "is efficiency sufficient on its own?" is conjoined with whether the rule itself sets the scale—through a cap or budget.

Substitution: We read substitution on two planes: on the one hand, as an analytic core grounded in exhaustible-resource economics—namely the Hotelling line's price-path logic and its assumptions about the elasticity of substitution; on the other hand, as a function of energy systems' infrastructural lock-ins, network externalities, and the material constraints of conversion technologies. This allows us to show that the proposition "substitution is possible" does not carry the same meaning in every period: at times it is primarily the price signal that enables substitution, while at other times standards, public investment, and grid architecture are what make substitution practically feasible (or, conversely, what constrains it). To reduce the risk of "saying everything at once," we consolidate substitution along a single conceptual axis: substitution is not an abstract market reflex but, more often than not, operates in tandem with an institutional and infrastructural apparatus.

Externality: In the classical Pigouvian framework, the externality problem concerns whether prices reflect social costs; in the energy domain, however, externality becomes layered. At the local level, it takes the form of air pollution and health impacts; at the geopolitical level, it includes the risks of supply disruption and the costs of strategic reserves; and at the global level, it emerges as the transformation of carbon emissions into a shared-sink problem (Pigou, 1920; Coase, 1960). The text argues that these layers are not articulated with equal weight in every period and that, especially in the climate era, the global externality has become more tightly coupled with debates on uncertainty and tail risks (in the Weitzman line). For this reason, we treat the "prices versus quantities" debate not as an arbitrary mix of neoclassical tools, but as a design problem of governing externalities under uncertainty.

Scale–distribution–allocation: Daly's ordering of scale–distribution–allocation is not presented in the text as the de facto dominant language of the mainstream; rather, it is employed as a normative design intuition that becomes especially visible once a budget/cap object gains salience in the climate era. The sequence—first specifying the ecological scale (the remaining carbon budget or a cap), then designing the distribution of burdens (rebates, fair sharing), and only subsequently carrying out allocation through market instruments—provides a useful lens for interpreting certain hybrid policy designs (Daly, 1996). However, we do not claim that this framework, on its own, represents all directions in the literature; in the sections that follow, the tension between this "Dalyan ordering" and the "optimal price" approach (e.g., the Nordhaus line) is made explicitly visible.

This conceptual map will be operationalized in the following sections around two questions: (a) while the semantic core of a concept remains stable, how do its meaning and policy effects change when it is anchored to different objects of measurement (reserves/flows/intensity/budgets)? and (b) which form of rule (standard, plan, tax, quota/cap, scenario/MRV) is legitimized by a given measurement object? In this way, the text does not claim to offer an all-encompassing "discursive atlas," but rather to demonstrate a bounded circulation pattern of selected concepts—one that can be traced through specific text types and instruments.

2. Jevons and the Language of Coal: The Efficiency Paradox, Imaginaries of Scarcity, and Public Opinion

When Jevons sat down to write *The Coal Question* in 1865, the concept of "energy" had only recently stabilized as a scientific category. The consolidation of thermodynamics in the 1840s and 1850s had established energy as a unified, measurable quantity: the common currency through which steam, heat, light, and mechanical force could be expressed and compared. Yet this scientific stabilization did not deliver a neutral technical term into the hands of political economists. As the intellectual histories of energy transition have consistently shown, the concept arrived in Victorian public culture already entangled with questions of national power, the moral significance of labor, and the political stakes of industrial dependence (Malm, 2016; Mitchell, 2011; Wrigley, 2010). The language of "energy" mapped readily onto existing anxieties about productivity, waste, and the finitude of national resources; what looked like a thermodynamic measurement was simultaneously a political diagnosis. Jevons inherited this charged vocabulary, and *The Coal Question* can only be properly understood as an intervention into a discursive field in which efficiency, consumption, and national vitality were already deeply entangled (Nef, 1932; Smil, 2017).

This genealogy matters for how we read *The Coal Question*. The efficiency paradox that Jevons articulated—that better engines might consume more coal, not less—was not merely a logical observation about price and demand. It was an intervention into a specific cultural economy of energy in which the question of "how much is left?" carried the weight of national survival, imperial competition, and the limits of industrial civilization. The argument landed in a discursive field already organized around energy as a measure of collective vitality and vulnerability—which is precisely why it generated a public "coal panic" rather than a narrow technical debate (Nef, 1932; Wrigley, 2010). Andreas Malm's reading of fossil capital and Timothy Mitchell's account of carbon politics both confirm that the transition to fossil fuels was from its origins a politically constituted process, not a neutral technical substitution; Jevons's text is legible as an early moment in which that political constitution became a matter of explicit public reasoning (Malm, 2016; Mitchell, 2011; Kander *et al.*, 2014).

The existing scholarship that has most directly engaged with Jevons's paradox provides indispensable orientation for the present analysis, while also clarifying where this article's contribution lies. Alcott's systematic examination of the rebound effect (2005) and Sorrell's comprehensive review of the evidence for backfire (2009) have established, within the economics literature, that the cost–scale mechanism Jevons identified operates across multiple channels—direct, indirect, and economy-wide—and that the magnitude of rebound is context-dependent and historically variable. This scholarship confirms that Jevons's principled argument was not a period curiosity but a durable conceptual contribution whose implications continue to be debated in the context of energy-efficiency policy and climate governance. The history of ecological and environmental economic thought has further clarified how Jevons's efficiency–scarcity nexus was taken up, transformed, and institutionalized across different intellectual lineages; Missemer's analysis of how Georgescu-

Roegen's bioeconomic legacy was reconstructed within degrowth and ecological economics (2017) and Allisson's toolkit for tracing intellectual legacies (2020) together provide a methodological grounding for the tracking logic this article adopts (Berta *et al.*, 2021).

What this literature has not foregrounded, however, is the question this article pursues: how did the conceptual structure of Jevons's argument—the efficiency–scale tension, the rebound logic, the reframing of scarcity as a problem of consumption intensity rather than reserve magnitude—circulate beyond the disciplinary boundaries of political economy and enter the administrative, regulatory, and public languages through which energy systems were subsequently governed? Alcott and Sorrell read the rebound effect as an economic proposition to be empirically assessed; Missemer and Allisson read intellectual legacies as histories of disciplinary reception. This article reads Jevons as a threshold text in the co-evolution of energy regimes and economic language—a text whose significance lies not only in what it argued, but in the translation work it performed across different "writing regimes": parliamentary debate, engineering discourse, public opinion, and the administrative languages of conservation, efficiency standards, and demand management that crystallized in later periods. This is not a claim that Jevons directly caused these later developments; it is a claim that the conceptual vocabulary he articulated—efficiency as a systemic problem, scarcity as intensity of dependence, scale as a governance object—proved unusually generative across successive energy regimes (Alcott, 2005; Sorrell, 2009; Missemer, 2017).

Jevons's 1865 *The Coal Question* constitutes an intervention that puts the industrial age's "energy reason" up for debate. Jevons objects to the assumption that more efficient fuel use will automatically reduce total consumption, summarizing the point as follows: "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption." (Jevons, 1865). The cheapness of coal, combined with efficiency improvements in machinery, may—contrary to commonsense expectations—not diminish aggregate coal use; insofar as it lowers costs, it can stimulate new uses and a broader scale of activity, thereby increasing consumption. This line of reasoning—now known as the "Jevons paradox" or, more broadly, the rebound effect—both sharpened imaginaries of scarcity in nineteenth-century Britain and reconfigured the ways in which efficiency, substitution, and conservation were articulated within economic public discourse (Jevons, 1865/1906; Alcott, 2005; Sorrell, 2009). Jevons's argument proceeds through three layers: (i) the material base—the energy density of coal and its specific linkage with the steam engine; (ii) the price–quantity channel—efficiency gains reduce effective costs and thereby expand demand; and (iii) innovation and market expansion—the emergence of new industrial processes and consumption patterns. In this way, a local technical proposition—"better engines, less coal"—can, in general equilibrium, flip into the outcome "more production, more coal" (Jevons, 1865/1906).

To understand why Jevons's paradox struck his contemporaries with such force, it is necessary to grasp what kind of economy Britain had been before coal became its primary energy base—and what coal had made possible. E. A. Wrigley's account of the English industrial revolution as fundamentally an energy transition provides the essential comparative frame (Wrigley, 2010). In what Wrigley calls the "organic economy," all energy ultimately derived from current solar income: the photosynthetic conversion of sunlight into biomass, whether through forests, agricultural land, or animal feed. This placed a binding constraint on the scale of economic activity: the amount of energy available was ultimately proportional to the land area under cultivation or woodland. By the seventeenth and eighteenth centuries, England had been pressing against this ceiling—timber shortages, rising fuel prices, and the diminishing returns of water and wind power were symptoms of an energy system approaching its natural boundary (Wrigley, 2010; Nef, 1932). Coal dissolved this constraint by opening access to a vast reserve of past solar income, stored in compressed organic matter over geological time. The crucial consequence was a radical decoupling of energy supply from land area: the energy yield of a coal-bearing region could exceed many times over what the same surface area could provide through managed woodland. Britain's industrialization was, in this specific thermodynamic sense, an escape from the organic economy's ceiling—but an escape that created a new and deeper dependency (Smil, 2017; Kander *et al.*, 2014). Once the machinery stock, the transport network, and the urban geography had been reorganized around the energy density of coal, there was no straightforward path back to the organic economy's operating logic.

It is against this background that Jevons's warning acquires its structural force. The question he posed in 1865 was not simply "how much coal remains underground?" but something more unsettling: given that the entire productive apparatus of British industry had been constructed in intimate dependence on coal's specific physical properties—its energy density, its compatibility with the steam engine, its centrality to iron and steel production—what would it mean if that dependence could not be dissolved through efficiency alone? Wrigley's framing makes visible what Jevons could only intuit: the paradox was not a quirk of price theory but a consequence of infrastructural lock-in operating at a civilizational scale (Wrigley, 2010). Efficiency improvements within the coal-steam complex could not escape the complex itself; they could only deepen it. This reading is consistent with Kander *et al.*'s comparative account of energy transitions across European economies, which suggests that the elasticity of substitution between energy carriers is historically specific and institutionally conditioned rather than a uniform technical property (Kander *et al.*, 2014).

The period's context turns this paradox into a public issue rather than a purely logical one. In the 1860s, Britain was the leading producer of coal worldwide; yet the accelerating expansion of iron and steel, railways, and steam shipping between the mid- and late nineteenth century helped diffuse the notion that "national power depends on coal stocks" (Wrigley, 2010). Jevons makes explicit the significance of coal for "national power" and identifies the pace of consumption—when coupled with the finitude of stocks—as the central risk; in this framing, scarcity is conceptualized not simply as the total underground reserve, but through the economy's intensity of coal-dependence and the tempo of growth (Jevons, 1865/1906; Smil, 2017). Accordingly, the "imaginary of scarcity" ceases to be a question of geology and becomes a political-economic problem of how deeply the production structure is embedded in energy. This perspective found public resonance in the 1865-66 "coal panic" debates and the subsequent official inquiries (the Coal Commission), where the discourse of efficiency diverged from the belief that "saving" would, by itself, yield automatic reductions (Nef, 1932; Wrigley, 2010).

The paradox's internal logic operates through cost and scale. When an efficiency improvement is measured as a narrow technical ratio—"less coal for the same output"—it appears to promise reduction. Yet, as Jevons emphasizes, once the total cost of production falls, the price of the final good declines; this expands demand both within existing uses and by enabling applications that were previously unprofitable. Moreover, efficiency gains generate not only "more of the same product" but also new classes of goods and services (for example, longer railway lines, faster freight, and more extensive urban lighting). This second channel constitutes the structural source of rebound (Jevons, 1865/1906; Alcott, 2005). These mechanisms—described in the modern literature through the distinction between direct, indirect, and structural (economy-wide) rebound—are already present in Jevons as an intuitive and integrated whole (Sorrell, 2009).

Jevons's efficiency argument also reframes the debate on substitution. In the context of the 1860s, no energy carrier "equivalent" to coal was on the horizon: a return to wood was technically implausible, and oil had not yet become embedded in the machinery stock and logistics of British industry. Accordingly, Jevons treats hopes of substitution largely as a matter of "buying time," and instead centers the discussion on the mutually reinforcing relationship between coal's cheapness/abundance and the scale of industry (Wrigley, 2010; Smil, 2017). In doing so, he anticipates—intuitively—what is now described as infrastructural lock-in: the co-evolved complex of machines, mines, transport networks, and skill sets aligned with coal narrows the elasticity of substitution in historically specific ways (Kander *et al.*, 2014).

At the level of public opinion, Jevons's language distinguishes between the "virtue of thrift" and the "systemic effects of saving." At the household or firm level, conservation can indeed reduce consumption; yet at the level of the national economy, efficiency may increase aggregate consumption through cost reductions and output expansion. This tension becomes, in contemporary parliamentary debates, a contest within moral economy between a "cheap coal policy" and the "rights of future generations" (Nef, 1932; Wrigley, 2010). Jevons's political prescription is therefore not, as is often assumed, to oppose efficiency as such; rather, he advances the argument that efficiency alone will not resolve scarcity, and that problems of "scale" and "speed" in public accounting—such as the energy appetite of exports, heavy-industry expansion, and railway investment—must be treated as a distinct object of governance (Jevons, 1865/1906). This emphasis reframes efficiency from a purely technical ratio into a problem definition that compels its joint consideration with scale and demand dynamics; as twentieth-century debates on energy conservation and system management generated administrative metrics (standards, load management, performance indicators), the same cost–scale tension re-emerged in the background of policy discussion (Hughes, 1983; Fouquet, 2008).

Jevons's text also confronts the period's limitations regarding measurement and evidence. In the 1860s, reserve estimates, production series, and price statistics were still in the process of standardization; operating within the deficiencies of an emergent regime of collective quantification, Jevons constructs a form of "logical–historical" reasoning. For this reason, his critics argued that he could be refuted by the sheer magnitude of coal reserves or by overestimating future technological leaps (e.g., more efficient pits, reduced transmission losses, newly exploited mining fields) (Nef, 1932; Smil, 2017). Nevertheless, the principled level of the paradox—namely that efficiency improvements reduce unit costs and can thereby expand demand—re-entered the agenda forcefully in the last quarter of the twentieth century as the macro effects of energy-efficiency policies came under renewed scrutiny. Khazzoom (1980) maintained that mandatory effiiency standards could "mechanically" overstate expected savings and generate rebound through channels such as increased use intensity and substitution; Brookes (1990) formulated a similar logic as a warning against the claim that energy efficiency alone could solve the climate problem. Saunders (1992) subsequently systematized this line within growth theory as the "Khazzoom–Brookes postulate." While later assessments emphasize that the magnitude of rebound is context-dependent and that "backfire" cannot be generalized, they also show that Jevons's cost–scale reasoning remains at the conceptual core of the debate (Sorrell, 2009; Ayres; Warr, 2009).

This case functions as a foundational point of departure for the study's thesis on the co-evolution of energy regimes and the language of economics. Jevons's reading of scarcity through the pace of consumption and the intensity of dependence reshapes the moral meaning of efficiency in the coal age: thrift as an individual virtue can, at the national scale, conflict with the expansion of scale itself. The same conceptual reorientation, in turn, bridges to the institutionalization of efficiency as a rationality of system operation (grids, load factors) in the era of electrification, to the supply-security discourse of the oil age, and to the rewriting of scale–distribution–allocation priorities in the climate era (Hughes, 1983; Wrigley, 2010; Smil, 2017; Daly, 1996). Jevons's language should therefore be read not only as an economist's warning but also as a rhetoric that reconstitutes coal's place in the public imagination—between abundance, power, and vulnerability.

Finally, the enduring significance of Jevons's intervention for "public reason" lies in making visible the distinction between efficiency and absolute reduction. This distinction is reformulated across periods through different instruments: under the electrification regime, efficiency is tied to system-operation metrics such as grid standardization and load management; in the crisis environment of the 1970s, conservation is articulated alongside energy-intensity targets and the repertoire of demand-side management; and from the 1990s onward, with the recognition that efficiency gains may not be sufficient on their own, it is debated in conjunction with price- and/or quantity-based climate instruments (Hughes, 1983; Graf; Steininger, 2019; Sorrell, 2009). At the same time, this lineage is not the single dominant approach in climate economics; it coexists—at times in tension—with lines that place efficiency at the center within an "optimal price" framework.

The Jevons moment established a conceptual vocabulary that subsequent energy regimes would inherit, transform, and partially discard. The efficiency–scale tension that *The Coal Question* articulated remained a structuring problem; but the material and institutional conditions through which that tension was managed changed decisively as coal's dominance gave way to a new energy carrier organized not around extraction and combustion but around transmission and distribution. Electricity did not simply replace coal as a primary energy source; it reorganized the problem-space of economic analysis itself. Where Jevons had asked "how much fuel remains, and at what rate are we consuming it?", the electrification era posed a different question: "how do we organize the continuous flow of a service—light, heat, mechanical power—across a network whose costs are predominantly fixed and whose demand varies by hour, season, and customer class?" (Hughes, 1983; Fouquet, 2008). This shift in the object of governance—from a depletable stock to a continuously produced and distributed service flow—brought a new cluster of concepts to the foreground of economic language: load factors, diversity factors, natural monopoly, peak-load pricing, and the tariff as a steering instrument rather than a cost-recovery mechanism. What the following section traces is not simply a new chapter in energy history, but a reconfiguration of the "concept–measurement object–rule" chain that Jevons had anchored to coal's specific thermodynamic and political properties (Wrigley, 2010; Smil, 2017; Hughes, 1983).

3. The Rationality of Electricity: Grids, Scale, and Planning

In this section, I treat "electrification" not primarily as a shift in primary energy sources—as with coal or oil—but as a reorganization of energy services (light, power, heat) through networks of generation, transmission, and distribution. Electricity is a secondary carrier and can be produced from different primary sources; yet the material and networked properties of the grid (standards, scale, natural monopoly, load curves) bring new clusters of problems into view within the language of economics.

The electrification wave of 1900-1930 taught policymakers and analysts to think of "energy" less as fuel and more in terms of services (light, power, heat) organized through grid logic. This transformation rendered especially visible—particularly in the literatures on public-utility economics and energy policy—three recurring shifts: (i) efficiency was no longer defined at the level of the individual machine but at the level of system operation (load factor, diversity factor, reliability); (ii) costs were conceptualized not as average unit production costs but as time-varying network costs; and (iii) pricing evolved from a "single tariff per kWh" toward demand-based charges and two-part tariffs. In this sense, electrification constituted a co-evolutionary field in which engineers' technical language of system management became a domain of translation for economists, while economic reasoning, in turn, institutionalized engineering's measurement–rule apparatus (Hughes, 1983; Hausman *et al.*, 2008; Nye, 1990).

The logic of the grid extends electricity's "economies of scale" across both space and time. As generating units (steam turbines, hydro) grow larger, unit costs fall; yet a crucial gain also derives from the diversity factor—namely, the non-coincidence of peak loads across different customer groups. The same installed capacity can be utilized more fully when demand is spread across the hours of the day. For this reason, the "load factor" becomes a central performance indicator for utilities: as the ratio of hourly energy sales to peak demand rises, capacity is used more efficiently. The engineer–manager Samuel Insull turned the pursuit of higher load factors—i.e., coupling scale with market design—into a managerial creed through the holding structures and contract regimes he built in early-twentieth-century Chicago; differentiated tariffs translated the grid's technical realities into the language of prices, ranging from block/step rates for large industry, to low initial kWh rates for households, to demand charges for commercial customers (Platt, 1991; Hausman *et al.*, 2008). These practices provide an early institutional anatomy of what economists would later term a "natural monopoly," defined by high fixed costs, low marginal costs, network externalities, and an expansionary, consumer-oriented coverage objective (Hannah, 1979).

In Europe, a comparable process of translation unfolded through different institutional pathways. In Germany, the *AEG–Siemens* ecosystem's construction of *Verbundwirtschaft* (an integrated, interconnected grid economy) rapidly scaled up generation–transmission coordination; intercity lines and regional associations began to operationalize the load-factor logic as part of a federal politics of networks (Hughes, 1983). In the United Kingdom, fragmented municipal power stations were tied together around the Central Electricity Board through the 1926 Electricity (Supply) Act, laying the foundations for 50 Hz standardization and regional transmission. In this setting, planning and standardization (frequency, voltage, metering) were treated as prerequisites of economic rationality (Hannah, 1979). In Russia, by contrast, electrification was positioned less as an issue of economic rationality than as the core of a national development myth: the GOELRO Plan translated the relationship between generation, industrial geography, and the grid into a discourse of regional development. The articulation of political slogans (electrification = modernity) with administrative engineering accelerated electricity's entry into economic thought through a language of "scale and plan" (Coopersmith, 1986).

During this period, as the concept of "efficiency" was translated from engineering into economics, its meaning shifted. Instead of the efficiency of an individual motor, system efficiency became the central concern. The grid is an apparatus that governs demand; accordingly, the tariff is not merely a mechanism of cost recovery but also a steering instrument. From the 1890s onward, John Hopkinson's logic of the two-part tariff (fixed + variable) was adopted by British municipal undertakings and, in subsequent years, evolved into a more differentiated structure in the United States through Insull's demand charges. These practices constituted practical antecedents of what would later be formalized in the economics literature as peak-load pricing (Hannah, 1979; Hausman *et al.*, 2008). In this way, the engineer's dictum—"peak hours are expensive"—is translated into the economist's proposition that "marginal cost varies over time"; a normative balance is then sought between public objectives (universalization, low-priced initial kWh) and cost-reflective accuracy (Nye, 1990).

Engineer–economist translations were evident not only in tariff design but also in the logics of investment and organization. The technical efficiency of large generating units advanced in tandem with the scale of finance and the structuring of markets. Holding-company forms, practices of cross-subsidization, and load-shaping strategies—such as pairing daytime industrial demand with nighttime residential lighting, or integrating "stray loads" (high-demand yet low-revenue groups) into the network—helped legitimize, within the language of economic policy, the notions of universal service and cross-subsidy (Platt, 1991; Hannah, 1979). In subsequent decades, this would become part of the economic rationale for public-utility law and for rate and profit regulation. In a sector characterized by high fixed costs and strong network externalities, regulated natural monopoly or public/municipal provision was typically favored over pure free entry (Hausman *et al.*, 2008).

The discourse of "rationality" surrounding electrification simultaneously produced a cultural economy. The luminous pavilions of world's fairs, municipal lighting projects, and advertisements for household appliances framed electricity not merely as an energy carrier but as a "measure of modern life." This visual–textual repertoire translated the diffusion of the grid into a civilizational index; the legitimacy of public investment and regulation was reinforced through the trope of progress "from darkness to light" (Nye, 1990). For economists, this made debates over distribution (who would be connected first, which tariff was appropriate for whom) and allocation (the alignment between costs and prices) unavoidable—especially where block tariffs that cheapened the low-income household's "first kWh" placed social objectives in tension with cost principles (Hannah, 1979).

The tension Jevons articulated in the coal age—between the individual-scale "virtue of thrift" and national-scale "expansion of scale"—is here rewritten in favor of grid rationality: conservation is no longer defined within a single machine, but through practices of load shifting and demand shaping. In the 1910s, large urban utilities' "cheap night electricity" campaigns aimed to smooth investment cycles by shaving peaks; what the later economics literature would describe as "intertemporal marginal cost" was, within engineering's shared practical reason, translated into campaign strategies and contract design (Platt, 1991; Hausman *et al.*, 2008).

Another enduring thread of this period is the legitimation of standardization and planning as constituent elements of economic rationality. Without frequency and voltage standards, regional pooling cannot be realized; without metering standards, tariff assessment and compliance cannot be secured. In the United Kingdom, the 1920s steps toward frequency unification (50 Hz) together with the transmission coordination established by the 1926 Act provide a powerful historical example of how, in a domain of limited competition, connectivity and coordinated scaling could reduce costs (Hannah, 1979). Germany's practice of interconnected grids and Russia's regional planning under GOELRO likewise reveal a shared economic insight across distinct political regimes. The economic "rationality" of electricity often hinges on the grid's degree of coverage, standardization, and operational coordination: while a larger network scale can make lower unit costs and greater supply reliability possible, these outcomes are ultimately conditioned by the technological mix and institutional design (Hughes, 1983; Coopersmith, 1986).

In sum, the rationality of electricity is constituted through the translation of engineering's metrics and operating logic into the language of economics: "technical" terms such as load factor, diversity factor, demand charges, standardization, and interconnection are rearticulated as "economic" concepts—economies of scale, natural monopoly, tariff design, and public service. This dual lexicon of 1900-1930 laid the theoretical groundwork for peak-load pricing, universal service commitments, and regulated monopoly regimes in the decades that followed; conceiving electricity as a grid, in turn, entrenched within economic thought the propositions that "efficiency equals system" and "cheapness equals design" (Hughes, 1983; Hausman *et al.*, 2008; Hannah, 1979; Nye, 1990).

The rationality of electricity bequeathed to subsequent energy regimes a specific institutional legacy: the idea that efficiency is a property of systems rather than machines, that costs are temporal and networked rather than unit-based, and that the tariff is a governance instrument as much as a price signal (Hughes, 1983). These propositions did not disappear when oil displaced coal and supplemented electricity as the dominant energy carrier of the postwar era; but they were significantly recontextualized. The grid's logic had been built around the management of continuous demand for a service produced and consumed simultaneously—a logic that made investment planning, standardization, and long-run load forecasting central governance problems. Oil's material properties—its high energy density, its storability, its compatibility with mobile combustion—shifted the centre of gravity from network management to supply chain administration (Smil, 2017; Kander *et al.*, 2014). The question was no longer primarily "how do we shape demand to match a fixed grid?" but "how do we secure a sufficient and stable supply of a commodity whose production is geographically concentrated and whose price is politically determined?" (Adelman, 1972; Yergin, 1991). This reorientation did not erase the system-efficiency legacy of electrification; it overlaid it with a new layer of concepts—abundance, security of supply, strategic reserves, elasticity of substitution—that reflected oil's specific logistical and geopolitical properties. The following section traces how this overlay reshaped the language of economic analysis during the long postwar boom.

4. The Oil Age: Abundance, Price Stability, Security, and the Institutionalization of "Energy Economic"

The period 1945-1973 is characterized, in many mainstream narratives of growth and industrialization, by the treatment of "energy" under the assumption of low-cost and secure supply. This assumption shaped not only policies of growth and industrialization, but also theoretical intuitions concerning pricing, competition, and security. Compared to coal, oil—owing to its high energy density, transportability, and the refinery–petrochemical chain—rapidly became dominant across manufacturing, transport, and heating. In the postwar reconstruction of Europe and Japan, "cheap Middle Eastern oil" was widely regarded as a key input to modernization, while in some countries fuel oil also gained a larger share in electricity generation (Yergin, 1991; Smil, 2017). This material transformation, in turn, rendered three themes more salient in economic language: expectations of abundance, the pursuit of price stability, and the emergence of security concerns.

The abundance narrative was sustained by two large-scale arrangements. First, it drew on the enormous supply potential unlocked by bringing low-cost Middle Eastern fields into production; second, it depended on the "administration" of supply by companies and regulators. In the United States, the Texas Railroad Commission (TRC) had, since the 1930s, prevented price collapses by prorating oil production—aligning output with demand and marketable production—which in practice created spare capacity and a domestic "swing producer" role (Adelman, 1972). Internationally, the multinational firms commonly referred to as the "Seven Sisters" managed the cost–price spread through the posted-price system and long-term offtake contracts. From the late 1940s onward, the "50-50 profit-sharing" regimes established in Venezuela (1943) and in the Middle East (e.g., the 1950 Aramco arrangement) standardized fiscal rent-sharing and stabilized the investment horizon (Blair, 1976; Yergin, 1991). This institutional architecture helped keep global nominal oil prices within a relatively narrow corridor throughout the 1950s and 1960s. In real terms, prices declined in many years, and oil was treated in policy documents as a prototypical cheap and elastically supplied input (Adelman, 1972; Smil, 2017).

Price stability was not merely a function of coordination among a few large firms. Economies of scale in the tanker fleet rapidly reduced maritime transport costs—even amid disruptions such as the 1956 and 1967 closures of the Suez Canal—while refinery technologies increased flexibility in the product slate. In this setting, economic discourse leaned less on the notion of a competitive market than on that of an administered market: prices were determined through bargaining and taxation, and surplus supply was managed via investment scheduling and spare capacity (Adelman, 1972; Blair, 1976). The emergence of OPEC in 1960—reflecting the desire of Venezuela and Middle Eastern producers to jointly shape the tax base and the posted price—aimed to rebalance this administered regime in favor of sovereign producers. Yet until the 1971 Tehran and Tripoli agreements, the broad contours of price stability were largely preserved (Yergin, 1991). This stability generated two consequences for economics: it reinforced the idea that energy could be treated as an input characterized by low marginal costs and wide substitutability—rendering the shift from coal to oil "natural"—while, at the same time, long-run scarcity debates in the Hotelling tradition were relegated to a secondary position in practical policy documents (Hotelling, 1931; Adelman, 1972).

The theme of security developed not in contradiction to abundance and stability, but as a complementary "background calculus." In the United States, the 1959 Mandatory Oil Import Program (MOIP) imposed quotas to preserve domestic production and strategic flexibility; in Europe, stockholding and supply-disruption scenarios were debated within the OEEC/OECD framework (Yergin, 1991). Short-lived supply disruptions triggered by the 1956 Suez crisis and the 1967 Six-Day War further institutionalized the security idiom; terms such as diversification, strategic stocks, flag carriage, and "dependence on the Middle East" appeared with increasing regularity in government reports throughout the 1960s (Mabro, 1973; Yergin, 1991). In parallel, a distinct field that would come to be labeled "energy economics" began to take shape: concepts such as energy intensity, fuel substitution, supply elasticity, stock/flow ratios, and investment lags formed an interface between engineering expertise and resource economics (Schurr; Netschert, 1960; Adelman, 1972).

The institutionalization of this field can be traced through four channels. First, sectoral monographs and cost studies analyzed the oil market outside the confines of competitive-market theory, grounding their accounts in institutional realities; Adelman's *The World Petroleum Market* clarified the techniques used to manage surplus supply and the economic logic of the posted-price regime (Adelman, 1972). Second, long-run energy studies adopted an economy-wide perspective. Schurr and Netschert's analyses of U.S. energy over the 1850-1975 period set out the historical anatomy of the energy–growth relationship; drawing on a distinction between inputs and services, they helped generalize an approach that conceptualized fuel in terms of its conversion into services such as light, heat, and power (Schurr; Netschert, 1960). Third, policy-oriented think tanks—most notably *Resources for the Future* in the United States—produced early systematic notes on instruments such as fuel taxes, demand management, and efficiency standards (Yergin, 1991). Fourth, on the eve of the 1970s, publication venues and associational infrastructures that consolidated energy economics as a research community gained strength: the launch of *Energy Policy* in 1973 and the emergence, in 1977, of an organization bringing energy economists together expanded the field's institutional foundations (Brown *et al.*, 2020; IAEE, n.d.).

The period's political economy connected oil's materiality to relations of power. Producer countries' efforts to expand their shares of taxes and rents collided with companies' investment schedules and with the economies of scale embedded in transport chains. By the late 1960s, OPEC had increased its capacity to push posted prices and tax rates upward; by 1971-1973, step by step, the way had been opened to "participation" arrangements and price increases (Blair, 1976; Yergin, 1991). This background indicates that the post-1973 rupture was not a sudden break, but the culmination of a gradual process of renegotiation. Subsequent scholarship in political science and history would emphasize how the geography through which oil is organized—via pipelines and maritime transport—reshaped power topologies and generated a "carbon politics" distinct from that associated with coal (Mitchell, 2011).

In the language of economics, this period entrenched the assumption that oil was not a tightly managed scarce input but an abundance administered at a distance. Industrial strategies were designed around the large-scale refinery and petrochemical complexes enabled by cheap oil; in electricity generation, fuel oil accelerated the shift from coal toward oil and gas in Europe and Japan; and the hegemony of the internal combustion engine in transport implied that even urban and spatial planning were adapted to the dominant energy carrier (Smil, 2017; Yergin, 1991). This infrastructure-dependent path would later make the practical limits of "elasticity of substitution" more visible. Price signals alone did not guarantee fuel switching; lock-in and sunk costs delayed economic adjustment. In the energy economics literature of the time, this reality was addressed through discussions of investment lags and time-varying marginal costs; the coal-age logic of "machine efficiency" was translated, in the oil age, into a concern with system and logistical efficiency (Adelman, 1972; Schurr; Netschert, 1960).

The institutionalization of a "security" discourse also reinvigorated debates over distribution and allocation. Questions such as who would bear how much of an interruption in supply under which shock, and how rules of solidarity and stock utilization should be specified, became the subject of regular simulations within the OECD after 1967. In Europe, minimum stockholding obligations and emergency burden-sharing mechanisms were subsequently tied to the coordination framework of the International Energy Agency (IEA), established in 1974 (IEA, 1994; Yergin, 1991). These practices indicated that, alongside the price mechanism, quantity-based arrangements—such as stock releases, quotas, and rationing—could become unavoidable under certain conditions. Yet this should be read not as a direct precursor of later quantitative instruments in the "carbon era," but rather as an accumulated body of experience that rendered visible the constraints under which rule design operates during energy supply disruptions.

To synthesize, the oil age contributed to making "energy economics" more visible within certain institutional domains—commission reports, policy think tanks, and applied resource economics—without, however, elevating it to a central position within the discipline. Managing abundance and stability encouraged institutional and logistical analyses more than competition-based models. While the security discourse expanded the state's domain around the triad of diversification, stockholding, and participation, firm–state bargaining—through posted-price arrangements and tax–rent regimes—also underscored that price could function as a political magnitude. This configuration provided fertile ground, in the post-1973 period, for concepts such as "energy intensity," "demand management," "strategic stockpiles," and "supply diversification" to rise rapidly within the language of policy. At the same time, the efficiency–conservation intuition inherited from the coal age was reinterpreted in the oil age through the lenses of systems design and security architecture (Adelman, 1972; Blair, 1976; Yergin, 1991; Smil, 2017).

The architecture of administered abundance that had sustained the 1945-1973 growth regime carried within it a structural fragility that the language of economics had largely chosen not to name. The assumption that oil was an elastically supplied, low-cost input—manageable through corporate coordination and sovereign bargaining—had encouraged industrial strategies, urban geographies, and capital stocks built around the internal combustion engine and the refinery-petrochemical complex (Adelman, 1972; Blair, 1976; Yergin, 1991). When that assumption collapsed in October 1973, the adjustment costs revealed what the postwar lexicon had suppressed: that infrastructural lock-in, once consolidated at the scale of an entire growth regime, constrains not only the elasticity of substitution but the very concepts through which policymakers understand the problem (Smil, 2017; Kander *et al.*, 2014). The shocks did not simply raise prices; they made visible a set of governance problems—energy intensity, demand-side management, strategic stockholding, supply diversification—that the abundance discourse had rendered analytically peripheral. Mitchell's account of how oil's pipeline-and-maritime geography had restructured political power topologies provides additional context: the institutional architecture of the postwar oil order had been designed for conditions of managed abundance, not for the crisis management that would now become necessary (Mitchell, 2011). The following section traces how these problems were rapidly institutionalized into a new policy vocabulary, and how that vocabulary, in turn, created the conceptual conditions for the carbon-era debates that followed.

5. The Post-1973 Transformation: Energy Intensity, Conservation, Supply Diversification, and the Conceptual Imprint of Crises

The oil shocks of 1973-1974 and 1979-1980 seriously undermined the assumption—entrenched during 1945-1973—of "cheap energy that is easily substitutable." These shocks added three recurring themes to the lexicon of energy policy: the objective of reducing energy intensity; the governance of conservation/efficiency through standards and programs alongside price signals; and the institutionalization of security of supply and planning as enduring policy problems. Together, these themes illuminate how perceptions of uncertainty and vulnerability were managed even as oil's material dominance persisted.

The first rupture occurred in intuitions about energy intensity. Whereas in the 1950-1973 period per capita energy consumption and per capita income rose together in many OECD economies, the post-1973 era marked a structural turning point. On the one hand, price signals and shifting expectations increased the responsiveness of energy demand; on the other hand, modernization within energy-intensive branches of manufacturing, compositional shifts in output toward services, and the accumulation of a more efficient capital stock generated a sustained decline in energy use per unit of GDP (Schurr; Netschert, 1960; Smil, 2017). It was insufficient to attribute the fall in energy intensity to "technical progress" alone: public policies systematically reshaped the demand side through standards and pricing reforms. In this way, "efficiency"—as in the electrification era of 1900-1930—again ceased to be merely a technical ratio and became a matter of rules and institutions.

The backbone of this institutionalization was the International Energy Agency (IEA), established in 1974, and the Emergency Sharing Mechanism within the OECD. By imposing on members a standard requiring oil stocks equivalent to at least 90 days of net imports, the IEA defined security not merely as a function of supply flows but as a function of stock–flow management. In the United States, the Energy Policy and Conservation Act (EPCA) of 1975 created the Strategic Petroleum Reserve (SPR); European countries implemented comparable obligations through national stockholding agencies. "Security" thus became a quantity-management problem that the price signal alone could not solve. In this sense, it constitutes a practical projection of the "prices versus quantities under uncertainty" debate (Weitzman, 1974). In moments of crisis, quantity instruments—stock drawdowns, sharing quotas, and demand-restraint campaigns—complemented market adjustment and helped contain secondary price spikes (Yergin, 1991).

Under the heading of conservation/efficiency, the policy repertoire accumulated along two axes. The first was performance standards. In the United States, the 1975 CAFE regulations imposed average fuel-economy requirements on new vehicles; by the late 1970s and early 1980s, standards for building insulation, boiler efficiency, and household appliances followed in successive waves (culminating in NAECA in 1987). Japan's Top Runner program in the late 1990s took shape as a dynamic model that translated best-available performance into the rule base (Gillingham; Stock, 2018). The second axis was demand-side management (DSM) by public-utility companies. Through the "negawatt" conceptualization (Lovins, 1976/1977), grid operators promoted peak shaving and load shifting via programs in lighting, heating/cooling, and process optimization. This revived—by translating it into customer contracting and incentive design after the late 1970s—the logic of system efficiency that we observed in the 1900-1930 electrification era. At the micro level, the "energy-efficiency paradox"—the gap between private rationality and the social optimum—was debated in terms of financing, information, and behavioral barriers (Jaffe; Stavins, 1994; Gillingham; Stock, 2018). In this way, a modern version of Jevons's rebound warning generated, within policy design, an intensified requirement for measurement and verification.

Supply diversification constituted a third pillar. The bringing onstream, in the late 1970s and 1980s, of fields such as the North Sea (UK–Norway), Alaska's North Slope, and Mexico's Cantarell expanded non-OPEC supply; the Soviet Union's pipeline trade directed toward Europe further diversified the geography of supply. Nuclear power expanded rapidly; a return to coal and, from the late 1980s into the 1990s, the diffusion of combined-cycle gas turbines altered fuel mixes in enduring ways (Yergin, 1991; Smil, 2017). Market architecture also changed. The growth of spot and futures oil markets in the 1980s (with NYMEX in 1983) accelerated the shift from the posted-price regime toward market-based price discovery. This, in turn, generated a new economic language centered on managing risk through financial instruments and on investment behavior shaped by expectations and volatility sensitivity (Adelman, 1995).

From a macroeconomic perspective, the mechanisms through which the shocks generated contraction alongside inflation (stagflation), as well as the role of investment lags, became enduring topics in the economics literature. While Hamilton (1983) empirically documented the synchronicity between oil shocks and recessions, the policy arena experienced oscillations between price controls and liberalization. In the United States, the price–allocation controls and two-tier pricing regimes implemented in the 1970s were abandoned through phased deregulation between 1981 and 1985; in Europe, tax-based policies that raised end-user prices helped entrench conservation more durably. These experiences illuminated how energy-intensive investments could be postponed through expectations channels and time-inconsistency problems, and how spare capacity could be internalized as a security cost (Yergin, 1991; Smil, 2017).

Another salient shift in this period was the expansion of measurement and performance indicators. Whereas debate in the 1950s-1960s often relied on volumetric metrics such as "barrels" and "BTUs," after the late 1970s indicators such as energy intensity, import dependence, days of stock cover, disruption costs, and the continuity of energy services (heat, mobility, lighting) became more prominent. This does not imply that welfare measurement was fully transformed; rather, it redistributed which magnitudes were treated as "critical" in policy evaluation.

A parallel can be drawn between the electrification era's emphasis on "system operation" and coordination prblems and the planning idiom that emerged here. Yet the post-1973 debate is not simply identical to the grid economics of electricity. Within the oil regime, the joint design of instruments—stocks, emergency sharing, standards, and supply diversification—strengthened a "design rationality" within specific subdomains.

In sum, post-1973 scholarship and policy practice articulated the discourse of efficiency/conservation with security of supply, institutional coordination, and problems of decision-making under uncertainty. This articulation increased interest in quantity-based instruments (stockholding obligations, quotas, targets) without displacing price-based approaches.

A more accurate formulation is that, from the late 1970s onward, the energy–economy lexicon brought the logics of “price” and “quantity” into more explicit coexistence within the same repertoire of governance.

6. The Carbon Age: Thermodynamics, Carbon Budgets, and the Emergence of the Language of Climate Economics

From the 1990s onward, the energy–economics lexicon underwent a gradual but consequential reframing. The concepts that had crystallized during the post-1973 decade—energy intensity, demand-side management, supply diversification—were formed in response to a disruption in *flows*: the interruption of oil supply, the volatility of prices, the insecurity of import dependence. The governance problem they addressed was, at root, a problem of managing quantities and expectations within a system whose physical limits were assumed to be distant. What changed after 1990 was not merely the addition of a new policy instrument, but a shift in the *object* being governed: from the management of energy flows under geopolitical uncertainty to the management of a cumulative atmospheric *stock* under physical constraint. This section traces three thresholds through which that shift was articulated—thermodynamic, budgetary, and institutional—and shows how each threshold reconfigured the “concept–measurement object–rule” chain that has structured the argument of this article.

The first threshold is thermodynamic, and its entry into economic language has a precise historical location. Nicholas Georgescu-Roegen’s The Entropy Law and the Economic Process (1971) constituted an intervention that challenged the neoclassical production function at its material foundations: if thermodynamic constraints are real, then energy is not simply another substitutable input, and the “efficiency” of a production process cannot be captured by a price ratio alone. Georgescu-Roegen’s timing was not accidental. Writing in the years immediately preceding the 1973 oil shock, he was responding to an already-visible tension between the growth economy’s material appetite and the limits of what he called the “fund-flow” structure of production—a tension that the abundance assumptions of the postwar era had rendered analytically invisible. His argument found little immediate traction within mainstream economics, but it established a lineage. Herman Daly's insistence on "scale first, allocation second" drew directly on this thermodynamic intuition; the ecological economics tradition that Daly helped institutionalize in the 1980s and 1990s kept the question of physical throughput on the agenda even as it remained marginal within the discipline. A more applied operationalization came with Ayres and Warr's exergy-based growth accounting (2009), which demonstrated that substituting "useful work"—the fraction of primary energy that performs actual mechanical or thermal service—for conventional energy-input measures could resolve a significant portion of the "productivity residual" that standard models attributed to disembodied technical change (Ayres; Warr, 2009; Kümmel, 2011).

What this lineage collectively introduced into economic language was not a new policy instrument but a recalibration of the *object of efficiency*: from a price ratio between inputs and outputs to a thermodynamically grounded measure of conversion loss. The significance of this recalibration for the carbon era is that it complicates the proposition that efficiency improvements can, on their own, dissolve physical constraints—a proposition that, as Section 3 showed, Jevons had already contested on different grounds in 1865. The two critiques are historically distinct but structurally convergent: both insist that the material properties of energy carriers impose limits that cannot be dissolved by better price signals alone (Ayres; Warr, 2009; Daly, 1996).

The second threshold is budgetary, and it is here that the shift from flow governance to stock governance becomes institutionally legible. The scientific basis for this shift was established with unusual clarity by Allen *et al.* (2009), who demonstrated that the magnitude governing global mean temperature increase is not the annual rate of CO_2 emissions but their *cumulative total*. This finding had a structural consequence for economic language: it displaced the policy question from "how much should we reduce emissions per year?" toward "how much can we emit in total before crossing a threshold?" The difference is not merely technical. A flow target is compatible with a welfare-maximizing price that adjusts emissions year by year; a stock target introduces a *ceiling*—a finite quantity whose distribution across time, sectors, and nations becomes the primary design problem. The concept of the "remaining carbon budget," synthesized and regularly updated in successive IPCC Assessment Reports, operationalized this ceiling as a calculable object: a number, expressed in gigatons of CO_2, that policy actors could count against (Allen *et al.*, 2009; IPCC, 2018; IPCC, 2021/2023).

The translation of this calculable object into a rule was not automatic. It required institutional infrastructure. The United Kingdom's Climate Change Act (2008) provides the clearest example of how the budget concept was converted from a scientific magnitude into a legally binding instrument of governance. The Act defines successive "carbon budgets"—legally enforceable caps on the net UK carbon account across multi-year periods—and places a statutory duty on the Secretary of State to ensure the account does not exceed the budget. The associated institutional architecture—the Committee on Climate Change (CCC), its regular progress reports, the carbon budget delivery plans—created a verification and accountability apparatus that made the budget not merely a target but an *auditable object of rule* (CCC, 2020; CCC, 2025). This is precisely the "concept–measurement object–rule" sequence that this article has traced across prior energy regimes: the load factor becoming a tariff design principle in electrification, the stockholding obligation becoming a security governance instrument after 1973, and now the remaining carbon budget becoming a statutory ceiling with monitoring, reporting, and enforcement attached.

The budgetary logic subsequently migrated into domains that had previously organized their risk frameworks around flow variables. The Network for Greening the Financial System (NGFS) climate-scenario framework, developed after 2017, translated temperature pathways into transition risk scenarios for financial institutions—presenting decarbonization trajectories explicitly against the background of a "limited carbon budget" (NGFS, 2023). The European Central Bank's 2022 climate stress test and the Bank of England's Climate Biennial Exploratory Scenario applied this scenario logic to balance-sheet assessment. These extensions indicate that the budget concept did not remain confined to energy or environmental policy: it migrated into the language of financial risk, where the question "how much atmospheric capacity remains?" became part of the calculus of asset valuation and prudential supervision. The pattern is consistent with what this article has argued across prior regimes: that economic language does not merely describe energy constraints but constitutes new objects of governance through the act of measurement (Hughes, 1983; Smil, 2017).

The third threshold is institutional, and it is organized around a question that Martin Weitzman did not originally pose for energy policy at all. "Prices vs. Quantities" (1974) was written in response to a specific regulatory conjuncture: the early 1970s expansion of environmental governance in the United States, the establishment of the Environmental Protection Agency (1970), and the debates surrounding the Clean Air Act Amendments of that year. The underlying problem was one of instrument choice under uncertainty—whether regulators who could not perfectly observe abatement costs should set a price (a tax or fee) and let firms choose their quantity of emissions, or set a quantity (a standard or permit limit) and let the price emerge from compliance behavior. Weitzman's formal result—that the welfare-superior instrument depends on the relative slopes of the marginal damage and marginal abatement cost curves—was, at the moment of its publication, primarily a contribution to the emerging literature on environmental regulation, not to energy economics. Its subsequent migration into climate policy discourse took decades and required a specific institutional catalyst (Weitzman, 1974).

That catalyst was the negotiation of the Kyoto Protocol (1997) and the design problem it created: how should emissions reductions be distributed across countries and sectors, and through which instruments? The "prices versus quantities" framework entered this debate not as a theoretical curiosity but as an operational vocabulary for comparing carbon taxes against tradeable permit systems. The distinction Weitzman had formalized—between price rules that fix the marginal cost of abatement and quantity rules that fix the total level of emissions—mapped directly onto the choice between a carbon tax and an emissions trading system (ETS). In the decade following Kyoto, this framework organized a substantial portion of the policy design literature: questions of banking and borrowing provisions, price floors and ceilings, the distribution of permits through auctioning or free allocation, and the management of price volatility were all articulated within the conceptual vocabulary that Weitzman's 1974 paper had established. By the time the EU ETS entered its first phase in 2005, the “prices versus quantities” distinction had become, in effect, the standard analytical grammar of carbon market design (Aldy; Stavins, 2012; Klenert *et al.*, 2018).

What this migration reveals—and what the history of the framework’s travels makes visible—is that the translation of a theoretical concept into a rule requires not only intellectual uptake but *metrological infrastructure*. The “prices versus quantities” debate only becomes practically meaningful once emissions are rendered into a countable, verifiable magnitude. The monitoring, reporting, and verification (MRV) systems that underpinned the EU ETS—facility-level emissions registries, third-party verification, the Union Registry—were not incidental to the instrument; they were its precondition. Without MRV, there is no quantity to cap, no allowance to trade, no price to discover. This dependency connects the carbon era’s instrument design problem to a longer pattern traced across this article: load factor measurement as the precondition of tariff design in electrification, stockholding accounting as the precondition of the IEA’s emergency sharing mechanism after 1973. In each case, the rule form is not prior to measurement—it is constituted through it (Hughes, 1983; IEA, 1994; Aldy; Stavins, 2012).

The subsequent development of the “prices versus quantities” debate in the climate context also generated a specifically *distributional* dimension that Weitzman’s original formulation had bracketed. Revenue recycling—the question of how carbon tax or auction revenues are returned to households and firms—became a central axis of political feasibility, as Scandinavian experience with carbon taxation and the design of cap-and-auction programs in California and RGGI demonstrated (Metcalf; Stock, 2020; Klenert *et al.*, 2018). This reintroduced, within instrument design, the “scale–distribution–allocation” sequence that Daly had proposed as a normative ordering: the ecological scale (the cap or budget) is fixed first, the distribution of burdens and revenues is negotiated second, and allocation through market mechanisms proceeds third. Whether or not policymakers explicitly invoked Daly’s framework, the logic of many hybrid designs—budget targets combined with auction revenues recycled as dividends or green investment—followed precisely this sequence (Daly, 1996; Stiglitz; Stern, 2017).

The three thresholds traced in this section—thermodynamic, budgetary, and institutional—share a common structure: each reconfigures the object of economic measurement and, in doing so, reconstitutes the legitimate form of rule. But this reconfiguration does not occur in a political vacuum. Timothy Mitchell's *Carbon Democracy* (2011) offers an indispensable analytical complement here: the shift from coal to oil was not merely a transition between energy carriers but a reorganization of the political topologies through which economic reason secures public authority. Coal's geography—concentrated, extractable by organized labor, interruptible through strike action—had made visible a particular form of democratic leverage; oil's geography—dispersed across pipelines and maritime routes, controlled through corporate and state logistical chains rather than mineshaft choke points—reorganized that leverage and produced a distinct configuration of what Mitchell calls "carbon politics." The preference for price-based instruments in mainstream climate economics—carbon taxes, tradeable permits, optimal carbon prices—over more direct quantity constraints is not merely a theoretical conclusion derived from welfare analysis. It is also a politically constituted choice, embedded in institutional landscapes where the flexibility of market mechanisms is compatible with the existing distribution of property rights, investment horizons, and corporate interests (Mitchell, 2011; Malm, 2016).

Philip Mirowski's analysis of how neoliberal thought reconstituted itself after the 2008 financial crisis provides a further layer (Mirowski, 2013). If market mechanisms are not simply efficient tools but ideologically defended dispositifs—institutionally reproduced through think tanks, regulatory agencies, and international organizations—then the "prices versus quantities" debate cannot be read as a purely technical contest. The choice of instrument encodes assumptions about where knowledge resides (dispersed in prices, or concentrated in regulatory capacity), what counts as legitimate governance (market signals or administrative targets), and whose costs and benefits are made visible. This is not to dismiss the technical literature on instrument design; it is to situate that literature within the co-evolutionary pattern this article has traced from the outset. The economic language of the carbon era—budgets, caps, carbon prices, MRV systems—does not merely respond to the physical constraints of the atmosphere. It is constituted through them, and in constituting them, it simultaneously reflects and reproduces the institutional arrangements through which energy systems are owned, operated, and governed (Mitchell, 2011; Mirowski, 2013; Slobodian, 2018).

In this sense, the carbon age does not represent a rupture in the co-evolutionary pattern traced across this article, but its most complex expression. The object of scarcity has shifted—from underground stocks to atmospheric absorptive capacity—but the underlying dynamic persists: the material properties of an energy constraint generate new objects of measurement, new measurement objects legitimate new rule forms, and new rule forms feed back into the social imaginaries and institutional arrangements through which energy systems are reproduced. What distinguishes the carbon era is the scale of the feedback loop and the explicitness of its political stakes. The question of which instrument governs carbon is simultaneously a question of who governs carbon—and that question, as this article has argued throughout, has never been purely economic (Mitchell, 2011; Weitzman, 1974; IPCC, 2018).

7. Comparative Synthesis and Conclusion

The co-evolution thesis advanced in this article is supported, across three comparative trajectories, by a recurring structural finding: as the material and logistical properties of energy carriers change, the concepts through which economic analysis frames its central problems—scarcity, efficiency, substitution, externalities—are reweighted, re-anchored to new objects of measurement, and re-expressed in new rule forms. The British trajectory illustrates this through the shift from coal's paradox of efficiency and scale to the grid's system-operation rationality and, subsequently, to the carbon budget's statutory ceiling; efficiency changes its referent in each period without losing its normative salience (Hannah, 1979; Hughes, 1983; CCC, 2020). The U.S. trajectory shows how an institutional architecture built for managed abundance—the TRC's prorationing regime, the posted-price system—was progressively overlaid, after 1973, by security governance instruments and, from the 1990s, by hybrid carbon-market designs in which price and quantity logics coexist without fully displacing one another (Adelman, 1972; Yergin, 1991;

Aldy; Stavins, 2012). The continental European trajectory suggests that planning and standardization traditions formed during electrification—Verbundwirtschaft, frequency unification, load-curve management—provided an institutional substrate through which the EU ETS's quantity-based architecture could subsequently be constructed and refined; the Market Stability Reserve represents, on this reading, a system-stability concern translated into carbon-market design (Hughes, 1983; Klenert *et al.*, 2018). The three trajectories do not converge on a single model; their comparative value lies precisely in the divergence they reveal between shared problems and locally inflected solutions.

Across these trajectories, three channels of co-evolution recur with sufficient regularity to warrant analytical attention, while three channels of divergence delimit the thesis's scope. On the common side: first, engineering metrics are systematically translated into economic categories—load factor becomes tariff design principle, stockholding ratio becomes security governance instrument, remaining carbon budget becomes statutory ceiling. Second, this translation is mediated through administrative and technical texts—electricity acts, energy commission reports, IEA emergency-sharing frameworks, IPCC assessment cycles—rather than through direct academic-to-policy transmission. Third, the instrument repertoire shows a layering dynamic rather than a succession: price-based and quantity-based instruments accumulate in the same governance domain, with the balance between them shifting as measurement objects change. On the divergent side: the United Kingdom's trajectory is distinguished by the role of standardization and statutory obligation in converting concepts into enforceable rules; the U.S. trajectory by the financialization of price discovery and the persistence of market-administrative hybridity; and the continental European trajectory by the planning-standardization legacy's partial translation into climate-market architecture. These divergences remind us that co-evolution is not a universal mechanism but a historically conditioned process whose outcomes depend on institutional path dependencies and political settlements (Hughes, 1983; Hannah, 1979; Yergin, 1991; Mitchell, 2011).

Five findings of broader significance emerge from this comparative-historical reading. First, "efficiency" is not a stable concept that travels unchanged across energy regimes: in the coal age it is structured by the rebound tension (aggregate versus unit consumption); in electrification by system-operation metrics (load factor, diversity factor); in the oil age by intensity and demand management; and in climate policy by its relationship to a cap or budget target. The concept's semantic core persists while its object of measurement and its policy referent change. Second, the object of scarcity shifts from depletable underground stocks (coal), to geopolitically disrupted supply flows (oil), to the atmosphere's absorptive capacity (carbon); and each shift displaces the dominant measurement language—reserves, flows, intensity, cumulative budgets—and the rule forms attached to it. Third, the price–quantity dilemma is not a timeless theoretical contest but carries institutional memory: the emergency stockholding and quota arrangements developed in the security-governance domain of the 1970s provided practical experience with quantity-based coordination that, while not a direct template, preceded and partially informed the design of carbon cap-and-trade architecture. Fourth, the social legitimacy of economic concepts is partly constituted through visual and textual repertoires—world's fair pavilions, electricity advertising, "energy independence" campaigns, carbon label schemes—and engineering sensibilities mediate public reason in ways that purely academic genealogies of ideas tend to understate. Fifth, infrastructural lock-in operates as a political-economic friction that reveals the historically conditioned character of substitution elasticities: the question "can we switch?" is always answered within a specific regime of co-evolved machines, skills, networks, and institutions, not in the abstract (Smil, 2017; Kander *et al.*, 2014; Wrigley, 2010).

These findings carry implications for how the history of economic thought might engage with the material history of energy systems, and for how contemporary policy debates might understand their own conceptual inheritances. The analytical vocabulary through which carbon governance is currently conducted—budgets, caps, carbon prices, MRV systems, net-zero pathways—did not arrive from outside history. It was constituted through the successive encounters between energy constraints and economic language traced in the preceding sections: the Jevons paradox that made efficiency a systemic rather than a technical problem; the grid rationality that embedded system-operation metrics into economic reasoning; the security governance that normalized quantity-based coordination instruments; and the carbon-budget science that displaced flow targets with stock constraints. Understanding this genealogy does not dissolve the design choices that confront policymakers today—the choice of instrument, the distribution of burdens, the pace of transition—but it does clarify the conceptual terrain on which those choices are made and the institutional path dependencies that constrain them. The question this article leaves open is an empirical and normative one: under which institutional conditions can the accumulated vocabulary of energy-economics co-evolution be translated into governance arrangements adequate to the physical scale and political urgency of the carbon constraint (Weitzman, 1974; Stiglitz; Stern, 2017; IPCC, 2018; Mitchell, 2011).

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