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Counting Carbon: Forward-Looking Analysis Of Decarbonization

Ryan Thomas Trahan

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Abstract

Policy analysis primarily looks backward to solve problems of individual and public choice. Analysts often seek to derive and draw marginal curves from existing data to extrapolate observed relationships into the future. Indeed, the White House Council on Environmental Quality recently issued a proposed rule that would, among other things, codify the concepts underlying these tools for environmental matters, i.e., requiring the considered effects of a proposed action to be "reasonably foreseeable" and meet a "reasonably close causal relationship." That proposal expresses a perspective with a long tradition, yet it presents a curious circumstance. Although marginal and statistical regression tools are among the most powerful methods for understanding past continuous change, their power and efficacy diminish when applied to discontinuous change, meaning disjointed or abrupt.

This article discusses the discontinuity problem that is inherent in reducing atmospheric greenhouse gas emissions (decarbonization). It suggests that combinatorics (i.e., mathematical analysis by counting and ordering) offers a useful methodology for evaluating that discontinuous change. Here, a simple counting approach (viz. Equivalent Substitution Analysis) considers, as two corresponding sets, the discrete number and combination of technological substitutions that are required for decarbonization. One implication of the analysis is that decarbonization need not be analyzed solely as a collective action problem. The article proceeds by exploring decarbonization conceptually and against archetypal

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modern analysis. The article concludes with a detailed case study of an electric utility, the nexus of decarbonization in the United States ("U.S.").

Introduction

> In the economic sphere an act, a habit, an institution, a law produces not only one effect, but a series of effects. … There is only one difference between a bad economist and a good one: the bad economist confines himself to the visible effect; the good economist takes into account both the effect that can be seen and those effects that must be foreseen.
>
> - Bastiat, 1850[2]

Policy analysis primarily looks backward to solve problems of individual and public choice. Analysts often seek to derive and draw marginal curves from existing data to extrapolate observed relationships into the future. Indeed, the White House Council on Environmental Quality recently issued a proposed rule that would, among other things, codify the concepts underlying these tools for environmental matters, i.e., requiring the considered effects of a proposed action to be "reasonably foreseeable" and require a "reasonably close causal relationship."[3] It is a perspective with a long tradition, and it appears superficially sensible. If effects are not reasonably foreseeable then how could they be accounted? Further, without a close causal relationship there is no strong mechanism between an action and its consequence. Nonetheless, although marginal and statistical regression tools are among our most powerful methods for understanding past continuous change, their power and efficacy diminish when applied to discontinuous change, meaning disjointed or abrupt.[4]

This article discusses the discontinuity problem inherent in reducing atmospheric greenhouse gas emissions (decarbonization). A general observation here is that decarbonization is a finite problem, one measured in discontinuous technological substitution. Decarbonization is a finite problem because we are informed of the specific quantities of greenhouse gas emissions that require reduction. It is discontinuous because the few

2. FRÉDÉRIC BASTIAT, SELECTED ESSAYS ON POLITICAL ECONOMY — WHAT IS SEEN AND WHAT IS NOT SEEN 1, 2-50 (Seymour Cain trans., ed. George B. de Huszar, introduction by F.A. Hayek (Irvington-on-Hudson: Foundation for Economic Education, 1995) (1850).

3. Update to the Regulations Implementing the Procedural Provisions of the National Environmental Policy Act, 85 Fed. Reg. 1684 (proposed Jan. 10, 2020) (to be codified at 40 C.F.R. pts. 1500, 1501, 1502, 1503, 1504, 1505, 1507, and 1508); *see also Fact Sheet: CEQ's Proposal to Modernize its NEPA Implementing Regulations*, EXECUTIVE OFFICE OF THE PRESIDENT COUNCIL ON ENVIRONMENTAL QUALITY (Jan. 7, 2020), https://perma.cc/2JEL-3U25 [hereinafter WHITE HOUSE COUNCIL ON ENVIRONMENTAL QUALITY PROPOSAL].

4. *See* discussion *infra* Part II.A.i-ii.

technological substitutes required to achieve those reductions either do or do not produce emissions (e.g., substituting electricity generated from a coal power plant for that of a wind farm), meanwhile the new non-emitting technologies have improved abruptly. The claim here is that a combinatorics type of analysis can augment individual decision-making and public policy, in part, because it can reveal unseen effects. Moreover, the equivalent substitution of necessary technological substitutes can be more readily evaluated. This analytical approach might be referred to as Equivalent Substitution Analysis (in contrast to, for example, Constant Elasticity of Substitution) or other new coinage; for present purposes it will be referred to as a counting analysis, a counting approach, or, simply, counting.

A counting approach considers the technological substitutions necessary for decarbonization as two corresponding sets: a countable group of relatively few technologies that are required to be replaced to reach the goal, and a set of new zero emission technologies that can be counted, ordered, and combined in different ways (permutations if you like) to meet such substitutions. This allows a counting analysis to be prospective. Rather than looking back to historical data, individuals and policymakers can take action targeted to specific elements of the existing set of technologies thereby accounting for any decarbonization action, whether small, large, or cumulative. Even a single substitution changes the composition of each set.

The structure of the article is as follows. Part I briefly sketches the problem of decarbonization. Part II reviews two conceptual problems of modern decarbonization analysis, and introduces a counting approach. Part III provides an empirical case study of an electric utility in the U.S. The case study illustrates at a more granular level how a methodology of counting can inform individual choice and strategic regulatory planning even where broad social consensus is not reachable. Electricity procurement stands at the nexus of decarbonization and such specificity is suggested as necessary to more accurate analysis.[5] The article conclusions are summarized in Part IV.

5. *See generally* ELINOR OSTROM, GOVERNING THE COMMONS — THE EVOLUTION OF INSTITUTIONS FOR COLLECTIVE ACTION, 14, 18–21 (1990) (introducing both theoretical and field empirical alternates to stylized assumptions regarding so-called tragedy of the commons) [hereinafter Ostrom]. Much modern data analysis eschews granular subject understanding due, perhaps, to a suspicion that knowing too much about the specific area introduces an opening for bias confirmation. It is an approach that can be fruitful but also lead to incorrect conclusions.

I. The Problem of Decarbonization in Brief

Greenhouse gas emissions in the U.S. originate overwhelmingly from the technologies used in the converging sectors of electricity and transportation, together with industrial heat and steam processes.[6] Substitution of these emissions-producing technologies then presents as the core problem of reducing greenhouse gas emissions (decarbonization), despite much commentary focused elsewhere.[7] The problem can further be expressed as a function, specifically the speed at which certain emissions-producing technologies are excluded by means of substitution.[8] All of which means just that decarbonization goals are time-sensitive, the technologies that produce emissions are in actuality quite limited, and therefore the problem of decarbonization can be stated as a query of how quickly a limited number of emissions-producing technologies are replaced.

The common refrain is that the needed technological substitutions should be made as efficiently as possible, concluding in disparate proposals for favored large-scale programs of infrastructure,[9] aspirational schemes of

6. *See* LEGAL PATHWAYS TO DEEP DECARBONIZATION IN THE UNITED STATES: SUMMARY AND KEY RECOMMENDATIONS (Michael B. Gerrard & John C. Dernbach, eds., 2018) [hereinafter PATHWAYS]. Of the 5.279 billion metric tons of carbon dioxide emissions in the U.S. in 2017, 4.92 billion metric tons were traceable to fossil fuel combustion, of which roughly 70 percent was attributable to the electric power and transportation sectors, with much of the remaining balance attributable to industrial heat and steam processes. Carbon dioxide emissions constituted approximately 80 percent of all greenhouse gas emissions in 2017, although other emissions like methane are many times more potent. *See* U.S. ENVIRONMENTAL PROTECTION AGENCY, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS 1990-2017, at ES-6 to ES-12 (2019), https://perma.cc/ ZP3W-QEVU.

7. *See, e.g.*, Cass Sunstein et al., *How People Update Beliefs about Climate Change: Good News and Bad News*, 102 CORNELL L. REV. 1431 (2017) (reading political polarization into belief structures about climate change); *see also* RICHARD THAYER & CASS SUNSTEIN, NUDGE: IMPROVING DECISIONS ABOUT HEALTH, WEALTH, AND HAPPINESS (2008) (describing a "paternalistic libertarianism" approach to social engineering human action). To the extent today's sustainable technologies are susceptible to practical and theoretical improvement in cost, performance, availability and so on (and whereas existing emissions-producing technologies are comparatively exhaustively farmed in such respects), broad social consensus and targeted opinion shaping may be inapposite.

8. If each element of the set of existing technologies has a correspondence with the elements of the set of new technological substitutes then a function is definitionally operable; however, a primary observation here is the lack of agreement on initial conditions and the failure of a limit due to the disjunctive characteristics of the elements. *See* Leonard Euler, *Leonard Euler's Elastic Curves*, 20 ISIS 72, 76 (W. A. Oldfather et al. trans., 1933).

9. *See, e.g.*, JB Ruhl & James Salzman, *What Happens When the Green Deal Meets the Old Green Laws* 44 VT. L. REV. 693 (2020) (arguing that colossal infrastructure projects in the U.S. are necessary to meet fundamental reductions in greenhouse gas emissions).

taxation,[10] quasi-markets,[11] or anticipatory capitulation.[12] Coercion accompanies each of these proposals.[13] Despite the concentrated effort, general agreement on decarbonization programs remains elusive as evidenced by the dearth of enacting legislation.[14] This is unsurprising as the human impacts of technological substitution can be expected to be

10. *See, e.g.*, William Nordhaus, *Designing a Friendly Space for Technological Change to Slow Global Warming*, 33 ENERGY ECON. 665 (2011) (arguing that a carbon tax is necessary to achieve an energy transition); *see also* JE Aldy et al., *Resolving the Inherent Uncertainty of Carbon Taxes*, 41 HARV. ENVTL. L. REV. F. 1 (2017); *see generally* Reuven S. Avi-Yonah & David M. Uhlmann, *Combating Global Climate Change: Why a Carbon Tax is a Better Response to Global Warming than Cap and Trade*, 28 STAN. ENVTL. L.J. 3 (2009).

11. *See generally* David B. Spence, *Naïve Energy Markets*, 92 NOTRE DAME L. REV. 973 (2017) (providing a useful reality check on overly neat, theoretical energy market resolutions to renewable energy adoption). A note of augmentation is that proponents of markets often misconstrue Hayek's thoughts on law and regulation; *see, e.g.*, FREDERICK HAYEK, THE CONSTITUTION OF LIBERTY 397–411 (1960).

12. *See, e.g.*, Emanuele Massetti & Robert Mendelsohn, *Measuring Climate Adaptation: Methods and Evidence*, 12 REV. OF ENVTL. ECON. & POL'Y 324 (2018) (claiming, as Mendelsohn has in other forms elsewhere, that adaptation can be effective at eliminating a large fraction of potential damage from climate change, if governments would take the actions prescribed); *see also* Richard A. Rosen & Edeltraud Guenther, *The economics of mitigating climate change: What can we know?* 91 TECHNOLOGICAL FORECASTING AND SOC. CHANGE 93 (2015) [hereinafter Rosen & Guenther] (describing, among other things, cost projection defects in integrated adaptation models that reduce incentive for policymakers to act).

13. *See* Ostrom, *supra* note 6. Large scale infrastructure often requires overriding certain individual and community preferences through the use of eminent domain to accommodate power transmission infrastructure. *See, e.g.*, James W. Coleman & Alexandra B. Klass, *Energy and Eminent Domain*, 104 MINN. L. REV. 659 (2019) (arguing for the necessity of eminent domain for electricity delivered to residential homes via transmission (distribution) lines); *see also* Yael R. Lifshitz, *Private Energy*, 38 STAN. ENVTL. L.J. 119 (2019) [hereinafter Lifshitz] (exploring the implications of the continued trend toward distributed electricity generation); *see also* Ryan Trahan, *Regulating Toward (in)Security in the U.S. Electricity System*, 12 TEX. J. OIL, GAS & ENERGY L. 2 (2017) [hereinafter Trahan, *Regulating*].

14. *See, e.g.*, CHRIS LAFAKIS ET AL., MOODY'S ANALYTICS, THE ECONOMIC IMPLICATIONS OF CLIMATE CHANGE (2019), https://perma.cc/QYS5-FCZH. Domestically, the state of dialogue is captured in the "Green New Deal," a statement of concepts provided by a pair of resolutions introduced by Alexandria Ocasio-Cortez and Ed Markey, respectively, H.R. Res. 109, S. Res. 59, 116th Cong. (Feb. 7, 2019) that would, among other things, require 100 percent domestic clean energy by 2030. Internationally, the Intergovernmental Panel on Climate Change (IPCC) provides scientifically considered recommendations, including that emitters reduce carbon dioxide emissions by 80 percent prior to 2050, measured from a base year of 2005; *see, e.g.*, SOLOMONE FIFITA ET AL., MITIGATION PATHWAYS COMPATIBLE WITH 1.5°C IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT, (2018) [hereinafter IPCC Special Report]. *See* Memorandum of Understanding Between the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) on the Intergovernmental Panel on Climate Change (IPCC) (1988), https://perma.cc/4Y8U-P7G2.

distributed unequally.[15] Additionally, individual preferences will naturally vary including by geographic and demographic factors.[16] As will be discussed, the lack of general consensus presents fundamental issues for analyses that prize efficient outcomes. A combinatorics approach (in its simplest form, analysis by counting and ordering) does not require broad social consensus.

II. Contrasts In Analysis

Efficiency and Marginal Analysis of Decarbonization

Marginal analysis might be characterized as the study of any action taken at the margin of change, a broad and encompassing field. Although it risks recursion, the present inquiry concerns only methodology rather than epistemology. Specifically, how is marginal analysis actually utilized to understand and regulate decarbonization and its technological inputs? Here, marginal approaches are used to measure rates of change (marginal rate analysis) between and among variables, with regressive analysis assisting where applicable. Marginal rate analysis describes what is reasonably foreseeable through the study of past rates of change, while statistical regression techniques might be characterized as helping tease out historic causal relationships.[17]

In the physical sciences a rate of change might describe how a chemical reaction proceeds in a particular environment, i.e., recognizing, based on observable historical data, a pattern in the changing relationship between variables.[18] Patterns in the social sciences, however, remain less reliably reduceable than in the physical sciences or are otherwise trivial. As will be illustrated, the modern study of marginal rates of change in the social sciences avoids trite conclusions by abstracting the effects resulting from human inputs. An example is the rate at which groups of humans, rather than any one individual, reduce or increase greenhouse gas emissions into the atmosphere generally. Analyzing group behaviors avoids déclassé

15. *See generally* Xavier Gabaix, *Power Laws in Economics: An Introduction*, 30 J. ECON. PERSP. 185, 196–197 (2016) [hereinafter Gabaix]; *see also* STEPHANE HALLEGATTE ET AL., WORLD BANK, MANAGING THE IMPACTS OF CLIMATE CHANGE ON POVERTY, 83–85, 91–97 (2016).

16. *See, e.g.*, Peter Howe et al., *Geographic Variation in Opinions on Climate Change at State and Local Scales in the USA*, 5 NATURE CLIMATE CHANGE 596 (2015); *see also* Gary M. Lucas Jr., *Behavioral Public Choice and the Carbon Tax*, 2017 UTAH L. REV. 115 (2017).

17. *See, e.g.*, Richard T. Carson & Kevin Novan, *The Private and Social Economics of Bulk Electricity Storage*, 66 J. OF ENVTL. ECON. & MGMT. 404 (2013).

18. *See, e.g.*, JOHN A. CONKLING & CHRISTOPHER MOCELLA, CHEMISTRY OF PYROTECHNICS 38–40, 116, 128–31 (3d ed. 2019) (describing variables in high energy reactions).

evaluations of each discrete, incremental unit of production, consumption, or otherwise, and (purportedly) much of the normative weight that goes with it. Marginal rate analysis is then freed to identify a continuous range of outputs traceable to a basket of historic inputs, smoothing the jagged edges of problematic micro action.

Notwithstanding methodological defects, the chief aim of such analytical tools is a desire to achieve an inchoate future efficiency, the lodestar of positivist thinking.[19] As noted in the introduction, the White House Council on Environmental Quality proposal for updating procedural mechanisms in the National Environmental Policy Act is an example, i.e., requiring the considered effects of a proposed action to be "reasonably foreseeable" and meet a "reasonably close causal relationship."[20] Viewed neutrally, that proposal reduces to a desire to efficiently balance (optimize) a desire to allow actions/projects to proceed faster against a preference to avoid certain environmental harms based on historical experience. Two specific problems associated with using marginal analysis in this way will be introduced shortly.

For now, a few words of context on the aim of efficiency are necessary, although a philosophical exploration far outpaces this discussion,. Very generally, a regulator could define efficiency as the state of affairs where it is not possible to take action that would improve upon a situation without also reducing the welfare of at least one of the parties concerned.[21] That view is likely to prove problematic as it conflicts even with a positivist perspective of regulatory action, the purpose of which is to allocate burdens and benefits unequally on and among different

19. *See, e.g.,* Avery Katz, *Positivism and the Separation of Law and Economics*, 94 MICH. L. REV. 2229 (1996); *see also* Ann Chih Lin, *Bridging Positivist and Interpretivist Approaches to Qualitative Methods*, 26 POL. STUD. J. 162 (1998); *see generally* Brian Leiter, *Legal Positivism as a Realist Theory of Law*, *in* THE CAMBRIDGE COMPANION TO LEGAL POSITIVISM (P. Mindus & T. Spaak eds., forthcoming 2020); *see also* Richard A. Posner, *The Economic Approach to Law*, 53 TEX. L. REV. 757 (1975).

20. *See* WHITE HOUSE COUNCIL ON ENVIRONMENTAL QUALITY PROPOSAL, *supra* note 3.

21. *See* VILFREDO PARETO, THE MIND AND SOCIETY 2063–79 (Arthur Livingston ed., Andrew Bongiorno trans., 1935) (1919); for a brief histography, *see* Fiorenzo Mornati, *Pareto Optimality in the work of Pareto*, 51 EURO. J. SOC. SCI. 65 (2013); *see also* FRANK J. GOODNOW, COMPARATIVE ADMINISTRATIVE LAW: AN ANALYSIS OF THE ADMINISTRATIVE SYSTEMS, NATIONAL AND LOCAL, OF THE UNITED STATES, ENGLAND, FRANCE, AND GERMANY, 9–14, 127, 135 (1893) (an early proponent of the idea that bureaucracy is unavoidable and that the efficiency of administration is of the utmost importance) [hereinafter GOODNOW]; *see also* Daniel A. Farber & Anne Joseph O'Connell, *The Lost World of Administrative Law*, 92 TEX. L. REV. 1137, 1188–89 (2014) (noting that a sole goal of efficiency may involve excessive sacrifices to, for example, the fairness of individuals).

constituencies.[22] Even seemingly "inert" or "fair" proposals would intentionally hurt some and help others; if not then such proposals would be ineffectual.[23] One immediate consequence is that considerations of efficiency remain normative and relative at center.

In the specific context of decarbonization normative concerns of efficiency show odd empirical contours. As one example, it is frequently observed that the ownership of the energy technologies that currently predominate (mining equipment, fossil generation plants, et cetera) has a correspondence with the distribution of societal wealth.[24] A consequence then of regulatory action promoting decarbonization is the potential for greater disruption to existing owners, especially as the pace of substitution of existing energy technologies increases.[25] Yet, goals of efficiency must be determined from some initial set of conditions. Today those conditions would include, in the U.S., the power distribution of wealth. All of which provides familiar explanation for why achieving "efficient" regulatory proposals, such as a neutral carbon tax, remain a remote prospect.

Nonetheless, if marginal analysis were simply a tool of narrowly-defined "efficiency" then a reasoned skepticism might question why such analysis should enjoy broad acceptance? The fundamental justification is simply that marginal rate analysis is a powerful tool for seeking efficient outcomes from the incremental, continuous type of change that experience indicates is most common. Decarbonization is not a problem of continuity, however.

No necessary social consensus or technical basis has formed that would allow the "efficient" pursuit of decarbonization. It is a contentious

22. *See generally* DWIGHT WALDO, THE ADMINISTRATIVE STATE: A STUDY OF THE POLITICAL THEORY OF AMERICAN PUBLIC ADMINISTRATION (1948) (undermining claims of inert efficiency by perceiving administrative action as inextricably and understandably political in nature, if not overtly so in execution).

23. *See generally* A.M. Sen, *The Impossibility of a Paretian Liberal*, 78 J. POL. ECON. 152, 155 (1970) (illustrating why liberal values might result in greater readership of certain books, even where such a result is Pareto inferior); *see also* KENNETH J. ARROW, SOCIAL CHOICE AND INDIVIDUAL VALUES 4, 7, 91 (1951).

24. *See generally* Gabaix, *supra* note 16; *see also* William K. Carroll & M. Jouke Huijzer, WHO OWNS CANADA'S FOSSIL-FUEL SECTOR? MAPPING THE NETWORK OF OWNERSHIP AND CONTROL, 3, 13–16 (2018) (showing that twenty-five entities account for approximately 40 percent of fossil revenues in Canada); *see also* UNEP FINANCE INITIATIVE, UNIVERSAL OWNERSHIP: WHY ENVIRONMENTAL EXTERNALITIES MATTER TO INSTITUTIONAL INVESTORS (2011) (an institutional explainer on the concept of universal ownership).

25. Or, as you like, this represents a process of partial rebalancing and incorporation of the externalities by which such owners originally acquired their share of wealth. Discussion of "stranded assets" (e.g., a power plant that fails to fully amortize because it is replaced with a new technology that does not produce emissions) may then reasonably be viewed as socially relevant to the extent that no economic substitutes are available to meet the consumptive needs of non-owners. Common argumentative strategies are employed to convert problems of asset ownership into social costs, although the course and pace of technological development appears to run counter to such efforts. *See infra* note 61.

and finite problem whose solutions are predicated on binary, discontinuous technological substitution. Thus, the use of abstraction in marginal analysis, often brilliantly handled,[26] is exposed in the context of decarbonization as a functional defect. Abstraction instead works best when initial conditions are stable.[27]

The difference is profound. By framing the problem of decarbonization as a question of societal efficiency, marginal rate analysis merely seeks optimization thereby understating the urgency that inheres in programs of decarbonization.[28] Simultaneously, as will be discussed, efficiency analysis overstates the social impact of necessary, but limited, technological substitutions and misconstrues the power of individual choice. As the later discussion in the case study describes, the new technological substitutes allowing for decarbonization are comparatively improved—cleaner, safer, less clumsy, more abundant, increasingly cheaper. This technological reality provides an independent normative basis (apart from efficiency) for improving the general welfare through the technological substitutions that are necessary to reduce greenhouse gas

26. Consider Zeno's paradox of motion and Russell's insightful response. A freeze frame of an arrow in flight would not show movement. If the arrow is not moving at that one specific instant, then when is the arrow moving, as each instant the arrow would be motionless. Russell observed that the arrow is not moving at any one instant but that motion, change, can be observed only through seeing the arrow "at" a certain point and then "at" another. The description of change for the arrow between two such points (or its existence at each point along the continuum), including its deceleration toward some finite limit, is a garden variety example of the calculus of marginal analysis. It may not ultimately describe reality, but its real-world importance is difficult to overstate. *See generally* WESLEY C. SALMON, CAUSALITY AND EXPLANATION 21-22 (Oxford University Press 1992).

27. *See, e.g.*, STEVEN STROGATZ, THE CALCULUS OF FRIENDSHIP (2009) ("Yet in another way, calculus is fundamentally naive, almost childish in its optimism. Experience teaches us that change can be sudden, discontinuous, and wrenching. Calculus draws its power by refusing to see that. It insists on a world without accidents, where one thing leads logically to another. Give me the initial conditions and the law of motion, and with calculus I can predict the future—or better yet, reconstruct the past.").

28. Programs of decarbonization reflect an effort to establish a correspondence between atmospheric inputs (of greenhouse gas emissions) and probabilistic risk outputs (catastrophic storms, sea level changes, et cetera). Such correspondences carry uncertainty in both measurement and forecast. The risks of *not* decarbonizing, however, are widely understood as existential, whether from an economic perspective or at a species level. It reasonably follows that if a particular social program is intended to result in sufficient decarbonization—otherwise why bother—then overcorrecting to the defined goal is the only reasonable type of error, i.e., Type 1 errors may reasonably be viewed as unacceptable in programs of decarbonization due to the qualitative character of the risk. *See generally* STEPHEN J. DECANIO, ECONOMIC MODELS OF CLIMATE CHANGE (2003).

emissions.[29] The commitment to and focus on incremental marginal methods persists nevertheless, and in two primary forms.

i. *The Issue of Continuity Bias*

Aggregated historical data often serves as an excellent input for constructing models of continuous change, with smooth curves reflecting a model of past quantitative experience. For the same reason, historical data are often an especially poor predictor, or contemporaneous descriptor, of discontinuous change. When an observed social relationship is disrupted—whether from adoption of substitute technologies, new regulation, or otherwise—relying on past quantitative data risks misconstruing the very nature of the problem. This is precisely because the phenomena or their inter-relationships are new and not reflected in past data, even when lags in compiling and analyzing data can be reasonably controlled.

Modern quantitative techniques twined to show continuity frequently exacerbate the risks. At the level of methodological technique this is well-understood; in calculus, it appears as the undefined derivative of peaked change, in economics it is described in the step change functions that discretely shift carefully plotted curves. There are few if any redemptive strategies for mitigating the problem of discontinuous change through marginal and regressive methodologies.[30] The following provides an archetypal example of modern policy analysis, illustrating the difficulty inherent in drawing best-fit lines through past data to extrapolate conclusions into the future.

Example: Continuity Bias in Analysis of Renewable Portfolio Standards

Renewable portfolio standards are a mechanism by which governmental subdivisions may establish a percentage, or some magnitude, of electricity generation that must be derived from renewable sources.[31] In the U.S., these arrangements are generally state-level programs, mostly enacted a decade ago, that were intended to incentivize the procurement of renewable electricity generation. Prior empirical study has indicated that the enactment of renewable portfolio standards tended to correspond with

29. *See generally* JOSEPH SCHUMPETER, BUSINESS CYCLES: A THEORETICAL, HISTORICAL, AND STATISTICAL ANALYSIS OF THE CAPITALIST PROCESS (1939) (Surplus values may be impossible in circumstances of perfect equilibrium but, largely fortunately, we never actually experience such conditions).

30. *See* David Lee & Thomas Lemieux, *Regression Discontinuity Designs in Economics*, 48 J. OF ECON. LIT. 281 (2010).

31. *See generally* Thomas P. Lyon & Haitao Yin, *Why Do States Adopt Renewable Portfolio Standards?: An Empirical Investigation*, 31 THE ENERGY J. 131 (2010).

normative preferences for cleaner energy.[32] It is nevertheless expected that analysts might ask whether renewable portfolio standards are, or were, "effective."

A recent working paper ("DRD Study") in economics answered the question by purporting to isolate the effect that such standards had on the cost of retail electricity, and on rates of renewables adoption.[33] To wit, if renewable portfolio standards did not increase uptake of renewable generation technologies, or were especially costly, then perhaps it could be concluded that they were not effective. The principal findings of the study were indeed negative: that renewable portfolio standards raise (are highly correlated with increased) electricity prices and are a comparatively expensive method to reduce greenhouse gas emissions.[34] It is a curious conclusion that requires some effort to conjure.

The exercise in the DRD Study was to take data measurements for twenty-nine states with mandatory renewable portfolio standards in two separate time periods: seven years and twelve years, respectively, after a state enacted a standard. Those results were then compared against states that did not enact renewable portfolio standards, in an effort to control for effects on retail prices and adoption rates.[35] However, the analyzed data set covered only the years from 1990 to 2015.[36] This is noteworthy as no twelve-year data could have been sampled for programs enacted after 2003. Meaning that perhaps 23 states, or 79 percent of the samples, could not have been included in the results, without adjustment. Furthermore, neither seven nor twelve-year data could have been included for standards enacted after 2008, meaning that five states, or 17 percent of the data set could not have been measured at all, without adjustment, according to the study parameters.[37] This represents breath-taking selective sampling, although alone, it is of limited interest to the issue being referred to as Continuity Bias. Consider, however, this approach to sampling in the context of the time period measured.

32. Thomas P. Lyon & Haitao Yin, *supra* note 31.

33. *See* Michael Greenstone et al., *Do Renewable Portfolio Standards Deliver?* (ENERGY POL'Y INST. UNIV. CHI., Working Paper No. 2019–62, 2019) [hereinafter *DRD Study*]. *See generally* Robinson Meyer, *A Very Important Climate Fact That No One Knows*, THE ATLANTIC (May 8, 2019), https://perma.cc/ R9HS-WQQL.

34. *DRD* Study, supra note 33, at 25.

35. *Id*. at 7, 8, 25.

36. *DRD* Study, supra note 33, at 13, 31.

37. The extent of this sampling problem is likely understated as there is no control group and it is not clear that "sampled" and "unsampled" data did not circulate temporally between the two categories studied. The authors gesture to one aspect of this problem in their caveats: *DRD Study*, *supra* note 33, at 24 ("[a] more broadly randomized control trial is unavailable here so there will always be a form of unobserved heterogeneity that could explain the results without [renewable portfolio standards] programs playing a causal role.").

Reasonable opinions may vary on the exact years but the time period from roughly 2010 to the present has come to be seen as the time of the "energy transition." One cause attributed to that transition is that from 2010 to 2019—a period commencing after the enactment of all the mandatory renewable portfolio standards in the DRD Study and extending past the end of the study's data set—the installed price of solar generation dropped by approximately 84 percent while wind generation dropped by 67 percent.[38] A more recent cost input change is that battery energy storage prices dropped by nearly 76 percent just from 2012 to 2018 (three years past the end of the data set but more than a year prior to the study's release).[39] Despite the attention these disruptive cost trends have garnered, the DRD Study design sought to remove the factor of temporality, albeit only for very old renewable portfolio standards.[40] This leads closer to the heart of Continuity Bias. A disclaimer from the study's abstract finishes the table setting: "[t]hese results do not rule out the possibility that [renewable portfolio standard] policies could dynamically reduce the cost of abatement in the future by causing improvements in renewable technology."[41]

It is sound that the DRD Study results do not rule out that possibility as even a cursory market review confirms that a process of adoption of

38. *See, e.g.*, LAZARD, LEVELIZED COST OF ENERGY 7-8 (version 13.0 2019) [hereinafter LAZARD]; *see also* GOLDMAN SACHS EQUITY RESEARCH: NEXTGEN POWER SOLAR TO TRANSFORM EUROPE'S ENERGY MIX (2018); *see also* RAN FU ET AL., NAT'L RENEWABLE ENERGY LAB'Y, U.S. SOLAR PHOTOVOLTAIC SYSTEM COST BENCHMARK: Q1 2018, at 7 (2018), https://perma.cc/YGS7-F9BL [hereinafter NREL BENCHMARK]; *see also* U.S. DEPT. OF ENERGY, WIND TECHNOLOGIES MARKET REPORT 69, https://perma.cc/3GMB-C9BR.

39. *See, e.g.*, *Battery Power's Latest Plunge in Costs Threatens Coal, Gas*, BLOOMBERG NEW ENERGY FIN. (Mar. 26, 2019), https://perma.cc/G28Q-FFZ7 (reporting that the levelized cost for lithium-ion batteries fell 35 percent to $187 per megawatt-hour since the first half of 2018); *see also* WOOD MACKENZIE, U.S. ENERGY STORAGE MONITOR Q4 (2018); *see also DRD Study*, *supra* note 33, at 1.

40. This latter development perhaps explains the DRD Study's hoary language about the claimed advantages of natural gas peaker plants that are, today, being replaced by battery energy storage solutions. *DRD Study*, *supra* note 33, at 3. The exhaustively studied problem of intermittency in renewables (the availability, or non-dispatchability, of solar and wind generation varies temporally according to the effects of solar warming) is not strongly linked with the use of gas "peaker" plants, which, in actuality, are now being consistently retired for economic reasons, replaced with better performing battery energy storage solutions. *See, e.g.*, PUB. UTIL. COMM'N E-4949, Energy Div. (Ca. 2018), https://perma.cc/QW2A-KS9D (approving the replacement of three natural gas peaker plants with battery energy storage for economic reasons).

41. *DRD Study*, *supra* note 33, at 1.

renewables dynamically led to improvements in cost and performance.[42] Stated differently, there was no singular scientific advance in photovoltaic solar panels or wind turbine technology over the past decade. Instead, a tight cycle of adoption resulted in iterative, incremental, hard-won improvements from scale, design, learning-by-doing, capital efficiency, and so on.

The Continuity Bias in the DRD Study's regressive analysis is no more nuanced than that: it treats dynamically changing technologies as static, then extrapolates to future relationships a story about past data. While the authors do expressly acknowledge that the central problem is likely dynamic change rather than the one studied,[43] the study's conclusions show that the impact of this observation is not well understood, the authors state that:

> While the potential damages from global climate change have been widely documented, it is almost self-evident that failing to cost-effectively reduce emissions will ultimately limit the magnitude of these reductions.[44]

In no sense is such a conclusion self-evident. Rather, the study simply arrived back at its normative docking station of short-run efficiency. By

42. *See, e.g.*, Goksin Kavlak et al., *Evaluating the Causes of Cost Reduction in Photovoltaic Modules*, 123 ENERGY POL'Y 700, 710 (2018) [hereinafter Kavlak & Trancik] (tracing reductions in solar pricing since 2001 to economies of scale and endogenous factors); *see also* Unni Pillai, *Drivers of Cost Reduction in Solar Photovoltaics*, 50 ENERGY ECON. 286, 291, 293 (2015) (tracing reductions in solar prices primarily to decreases in polysilicon prices and usage). *See also* Harry Apostoleris et al., *Evaluating the Factors that Led to Low-Priced Solar Electricity Projects in the Middle East*, 4 NATURE ENERGY 833 (2019) (reviewing evidence that the input of cost of capital is (and was) a chief determinant for renewables deployment that materially improves with scale); *see also* FRANKFURT SCH. OF FIN. & MGMT. – U.N. ENV'T PROGRAMME, GLOBAL TRENDS IN RENEWABLE ENERGY INVESTMENT 16–18 (2018), https://perma.cc/HC6F-QKT9 (reviewing favorable wind and solar pricing, cost, and deployment trends from increased investment). *See* NREL BENCHMARK, *supra* note 38, at 7 (The National Renewable Energy Laboratory provides a well-known annual longitudinal cost breakdown of solar prices that provides further support for this perspective, illustrating the importance of "soft" cost inputs); *see also* SCOTT MOSKOWITZ, GTM RESEARCH, *Trends in Solar Technology and System Prices* (2018); *see generally* BRONWYN H. HALL & BEETHIKA KHAN, *Adoption of New Technology*, *in* NEW ECON. HANDBOOK 3, 5 (2003) [hereinafter HALL] ("Yet it is diffusion [widespread adoption] rather than invention or innovation that ultimately determines the pace of economic growth and the rate of change of productivity.").

43. *DRD Study*, *supra* note 33, at 24 ("The coincidence of the proliferation of policies that support renewable energy and the decline in solar prices over the last decade are consistent with the possibility of such spillovers. However, research that isolates the magnitude of any such spillovers from other factors is probably best described as emerging, making this is a rich area for future research.").

44. *DRD Study*, *supra* note 33, at 25.

contrast, the experience of technological adoption in this context (or capital investment in a related context)[45] guides that short run cost-effectiveness is largely beside the point, or at least far from the near-tautology the authors perceive. Certainly, a conclusion of the necessity of cost-effectiveness cannot be said to follow from the regressive analysis that proceeds it in the DRD Study; indeed, the opposite seems a much more reasonable finding.

To more understand this aspect of the issue of Continuity Bias from another perspective, consider the methodology of the DRD Study against the proposed rule of the White House Council on Environmental Quality, i.e., that environmental effects should not be considered unless there is a "reasonably close causal relationship" to the proposed action.[46] The authors of the DRD Study transparently acknowledged that it was likely that renewable portfolio standards caused, "improvements in renewable technology."[47] Yet, understandably, they could not describe the new relationship using regressive methodologies operating on superannuated data. In substitute, the DRD Study told a story about continuous change in a time period of abrupt technological transition. This is analogous to the methodological deficiencies that the proposed rule from the Council on Environmental Quality would codify, i.e., where only what can be shown by marginal and (statistical) regressive methodologies that previously happened can be considered, notwithstanding empirical evidence to the contrary.[48] The DRD Study serves as a straight-forward example of what is being referred to as Continuity Bias—here, misexplaining a discontinuous reality by pairing selectively-sampled superannuated data together with overriding assumptions of continuity.

ii. *The Issue of Abstraction Bias*

Abstraction is the label used here to refer to the level and manner in which the problem of decarbonization is formulated. The claim is that the typical manner of abstracting the problem of decarbonization leads to bias because marginal rate analysis requires a continuum to make non-trivial observations and predictions about human action. As a facile example, consider if, next Tuesday, your good friend installs solar panels with battery energy storage and also purchases an electric car. This circumstance is

45. *See generally* R.H. Coase, *The Marginal Cost Controversy*, 13 ECONOMICA 169 (1946) (describing the need to separate the delivery and generation price of electricity and warning against blindly setting marginal price to marginal cost in contravention of other considerations); *see also* George Priest, *Ronald Coase, Firms and Markets* 8–9, 11–13 (YALE L. & ECON., RSCH PAPER NO. 510, 2014), https://perma.cc/VFK5-37XS.

46. *See* WHITE HOUSE COUNCIL ON ENVIRONMENTAL QUALITY PROPOSAL, *supra* note 3.

47. *DRD Study*, *supra* note 33, at 1, 24, 25.

48. *See* discussion *infra* Section II.B.; *see also* WHITE HOUSE COUNCIL ON ENVIRONMENTAL QUALITY PROPOSAL, *supra* note 3.

problematic for establishing a marginal rate of change. On Monday, the day prior, your friend was producing many tons of yearly direct emissions, but none the next day.[49] That binary change presents a quandary: your friend's rate of emissions went from some number to zero, it presents as discontinuous.

Marginal rate analyses sidestep the challenge by means of abstraction. Specifically, the discrete actions of an individual (solar panels with battery energy storage and an electric car) are reconsidered in the aggregate, e.g., what is the effect on the efficiency of the electricity system as a result of such actions? Through iteration, individual and cumulative effects (a defect of macro integration) are consistently discounted in the analysis.[50]

Consider the issue of Abstraction Bias directly in the context of an electric utility. Most commentary in the electric utility industry assumes that the relationship between electricity generation and greenhouse gas emissions reduces to a positivist question of efficiency. Specifically, how can a bad consequence (emissions) be minimized while a good outcome (electricity generation) is maximized? Electric utilities typically report a single average emissions metric measured over the duration of a year.[51] Yet, adjusting a rate of emissions efficiency requires incremental change in either emissions or generation, as those variables relate to one another. If the same electric utility introduces a new power plant that does not emit pollutants, then this efficiency measure is not operable at the discrete level.

Like your friend, above, the substitution is discontinuous: there are zero direct emissions per unit of electricity generated from a new renewable generating plant such as a wind or solar farm.

Modern marginal rate analyses compensate for the disruption by abstracting the effect of the renewable power plant to the system level, e.g., the utility's power plant portfolio, the local electricity delivery system, or perhaps the regional market. Here, marginal rate analysis remains apposite as the new zero emissions plant simply causes a change (a jagged edge) in the overall (smooth) pattern of the electric utility's aggregate generation. From a marginal perspective, nothing more has occurred than an incremental change in the emissions efficiency metric of the electric utility.[52]

49. "Direct" in this case is intended to approximate the concept of Scope 1 emissions.

50. *See generally* Kevin M. Stack & Michael P. Vandenbergh, *The One Percent Problem*, 111 COLUM. L. REV. 1385 (2011); *see also* Michael P. Vandenbergh & Anne C. Steinemann, *Carbon Neutral Individual*, 82 N.Y.U. L. REV. 1673 (2007).

51. *See* discussion *infra* Part III.

52. This type of exercise is used by electric utilities to demonstrate progress toward goals of decarbonization by, among other things, highlighting the improved emissions efficiency from substituting natural gas for coal. Regrettably, those implementations often present as immediately efficient while ensuring that decarbonization goals cannot be timely met because the deployment of natural gas establishes a base level of emissions incompatible with goals of decarbonization.

One apparent issue with relying on a marginal rate metric in this way is that it cannot capture energy conservation and energy efficiency, because differential rates do not measure what is not there. Restated, displacement of demand with energy efficiency does not *directly* impact a utility's rate of emissions at the margin because kilowatt hours that are never used are not a variable in the calculation. Such metrics, while frequently understood to be a neutral, fail to directly account for an entire class of approaches to decarbonization.

A less obvious effect is that the abstraction from the micro to the macro (system level) transmutes the question of which electricity generation and delivery technologies should be selected. It converts a consideration of discrete technological choice (is this renewable power plant or photovoltaic panel on this house a good thing) into a problem of system analysis (is the impact of that renewable power plant or solar panel on the overall electricity system a good thing). The lodestar of "efficiency" serves as both the justification for moving the analysis from the micro to the macro and as the rubric for evaluating the resulting technology options. Once the objective is changed to "system efficiency," the renewable power plant or solar panel can be characterized as detrimental.[53]

Abstracting the problem from the micro removed an evaluation of whether the effect on the system *needs* to be realistic, whether it remains necessary. Technological substitution in this context carries with it at least two types of optionality. The first at the level of the technological artifact itself (which device should we select) and, second, at the system level as a disruptive micro change introduced new options for replacing part of the system (how should electricity be delivered). Rather than representing an abstract example of the vagueness paradox, this is descriptive of one way in which disruptive technologies may change fundamental socio-technical processes.[54]

As detailed later, the electric utility sector consists of remarkably few emissions-producing inputs, a circumstance arrived by way of historical technological limitations.[55] For this reason and others, many of the seminal thinkers on electricity procurement were sure that the electricity system

53. *See generally* Frank W. Geels, *Regime Resistance Against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective*, 31 THEORY, CULTURE & SOC'Y 21, 21–40 (2014) [hereinafter Geels]; *see also* Ivan Penn, *Florida's Utilities Keep Homeowners From Making the Most of Solar Power*, N.Y. TIMES (July 7, 2019), https://perma.cc/KG2J-RNZ6.

54. *See* Geels, *supra* note 53; *see also* Dorothy Edgington, *The Philosophical Problem of Vagueness*, 7 LEG. THEORY 371 (2001).

55. *See generally* THOMAS P. HUGHES, NETWORKS OF POWER: ELECTRIFICATION IN WESTERN SOCIETY, 1880-1930 (1993) [hereinafter HUGHES].

itself could never be different.[56] Yet, it already is.[57] It reasonably follows that substituting out even more technological elements may further alter the structure of the system itself, due to iterative improvements resulting from adoption of new technology. This view is bolstered by an understanding of certain technical aspects of electricity networks.[58]

A. Normative Counting Analysis

The discussion above reviewed defects of certain marginal (and statistical regression) tools as applied to decarbonization. Such approaches were shown to be predicated on unexamined assumptions of the need for social efficiency, general cost effectiveness, and the permanency of existing systems. A counting analysis, by contrast, is intended as a purely normative approach. It is the expression of a preference for fewer greenhouse gas emissions made at the individual, community, or more aggregated level. Although decarbonization is often framed as a collective action problem, a counting analysis reveals that such characterizations are not strictly necessary, with consequences for strategic planning intended to reduce greenhouse gas emissions.

i. *Existing Set, New Set*

Consider the set of discrete technological artifacts that must be substituted ("Existing Set") in correspondence with the second set of new substitute technologies ("New Set"). The Existing Set of fossil technologies has been counted, it is definite subject to periodic discrete additions and subtractions. The New Set, while less definite, is today well described, e.g., wind, solar, battery energy storage, electric vehicles.[59]

56. *See, e.g.*, *id.* at 1. ("A great network of power lines which will forever order the way in which we live is now superimposed on the industrial world").

57. It took roughly 40 years (1976 to ~ 2016) for one million distributed solar installations to be reached; and three years (2016 to 2019) for the second million distributed installations. *See* WOOD MACKENZIE, SOLAR MARKETS—THE UNITED STATES SURPASSES 2 MILLION SOLAR INSTALLATIONS (2019) [hereinafter WOODMAC DISTRIBUTED SOLAR REPORT].

58. *See* discussion *infra* Section III.A.i.

59. This circumstance is recent. Less than a decade ago it was still reasonably uncertain which technologies could deliver on decarbonization goals. The interim improvement in the New Set substitutes occurred so quickly, however, that the debate is no longer live. This is not the same as saying new technologies will not be invented or some other perilous future casting. Rather, the New Set of technologies have abruptly become capable of achieving goals of decarbonization, and those goals include inherent time constraints. This is the type of uncommon discontinuous change that historical tools, like marginal rate and regressive analysis, are constructed to miss.

As such, the types of elements in the New Set may be treated as generally known, albeit dynamic in application.[60] In the context of certain transportation technologies, a direct bijection may be possible between the Existing Set and the New Set, e.g., for the subset of passenger vehicles, one electric car corresponds to the replacement of one internal combustion engine car. For electricity generation and energy applications, a correspondence will still mostly obtain although potentially in different (non-injective) proportions.[61] Counting describes the exchange of a limited number of elements between these two sets because decarbonization is a finite goal.

The sets are, of course, different. Replacing the Existing Set is defined as a normative exercise; the corresponding changes in the New Set are technologically driven in the manner described. The improvement and transition of the New Set is expected to be driven by entrepreneur, firm, and market processes influenced by, among other things, governmental subsidies and penalties, including beneficial and detrimental regulatory actions.[62] This framework naturally leads to a question as to whether general differences can be observed, at the set level, as between the Existing Set and the New Set?

ii. *Improvement Gap*

Ignoring emissions, a principal difference between the two sets is the practical and theoretical potential for improvement (Improvement Gap) of the constituent technological artifacts. The Existing Set consists of artifacts that are reliant on physical processes that have been more or less maximized in practical performance, e.g., steam turbines for boiling water, internal combustion engines, and so on. Indeed, even the *theoretical* range of

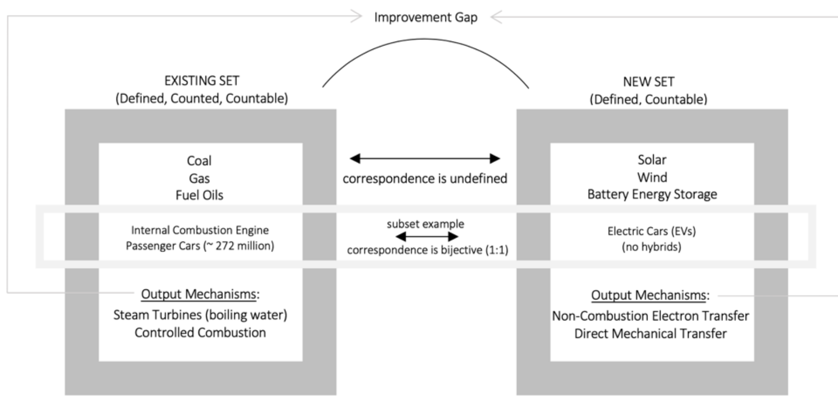
60. Allocating resources to truly speculative research rather than iterative design improvement, demand-creation, or direct and immediate technological substitution expresses the opinion that design, manufacturing, and scale improvements of existing technologies are likely to be so *economically* inadequate that a material percentage of the time window and investment available to decarbonize should be spent casting about for invention. Proponents of "blue sky" inventions are therefore making two related bets, a parlay: brand new technologies will be so improved as to overcome the time value problem of carbon emissions, and such inventions can be realized with time to spare for necessary social adoption. *See, e.g.*, Carlos Anchondo, *Bill Gates-Backed Startup Claims Solar 'Breakthrough.' Is it?*, E&E NEWS (Nov. 20, 2019), https://perma.cc/9FKC-2LDV.

61. The problem of decarbonization is a function of the speed at which a finite number of emission-causing technologies are excluded by means of substitution out of the Existing Set from the New Set.

62. *See generally* JOSEPH SCHUMPETER, THE THEORY OF ECONOMIC DEVELOPMENT (Redvers Opie trans., 1934).

performance of the technologies in the Existing Set is established and largely realized.[63]

The New Set is essentially opposite. Its technological artifacts remain susceptible to very substantial improvement, both practical and theoretical.[64] As described, the pace of practical improvement is largely dependent on increased adoption. Figure 1 provides a simplified visual representation of the Improvement Gap.



63. Internal combustion engines, steam turbines, and other established technologies are well farmed. Notably, the natural gas revolution, as it were, was propelled primarily by technological gains in procurement, not improvements in generation. *See, e.g.*, Xinglin Lei et al., *Fault Reactivation and Earthquakes with Magnitudes of up to Mw4.7 Induced by Shale-Gas Hydraulic Fracturing in Sichuan Basin, China*, 7 SCI. REP. 1 (Aug. 2017), https://perma.cc/PCG5-9ZZA; *see also* Richard S. Middleton et al., *The Shale Gas Revolution: Barriers, Sustainability, and Emerging Opportunities*, 199 APPLIED ENERGY 88, 88-95 (2017).

64. Take the theoretical limits of solar generation as an example, as the potential for practical gains are relatively more obvious. *See generally* William Shockley & Hans J. Queisser, *Detailed Balance Limit of Efficiency of p-n Junction Solar Cells*, 32 J. APP. PHYSICS 510, 519 (1961), https://perma.cc/MX2Q-Q8BL (describing an efficiency limit of ~ 30 percent and observing that the highest in-lab efficiency value achieved at that time was 14 percent); *see also* Markus Einzinger et al., *Sensitization of Silicon by Singlet Exciton Fission in Tetracene* 571 NATURE 90 (2019) (describing a method, in a manner analogous to cogeneration, where excess heat from high energy blue and green light is used to excite more than one electron, resulting in potential single cell efficiencies of perhaps 35 percent, a fundamental change); *see also* Tristan Deppe & Jeremy Munday, *Nighttime Photovoltaic Cells: Electrical Power Generation by Optically Coupling with Deep Space*, 7 CS PHOTONICS 1, 1-9 (2019); *see also* Fahhad H. Alharbia & Sabre Kais, *Theoretical Limits of Photovoltaics Efficiency and Possible Improvements by Intuitive Approaches Learned from Photosynthesis and Quantum Coherence*, 43 RENEWABLE AND SUSTAINABLE ENERGY REVS. 1073, 1074-1076 (2015) (providing a clear recitation of the state of then-current and still-relevant technological solar progress, including multiple-cell layered approaches, prior to main discussion on quantum aspects and photosynthesis potentially applicable to photovoltaics); *see generally* JENNY NELSON, THE PHYSICS OF SOLAR CELLS 291, 297 (2003).

Figure 1: Technologies Determining Greenhouse Gas Emissions: Simplified Set Comparison.

Counting gives rise to the qualitative observation of the Improvement Gap by expressly recognizing that elements of the Existing Set must correspond to the New Set. A counting approach is therefore always prospective as it must evaluate technological improvement as it is or will be, rather than how it has been. An effort might be made to convert the Improvement Gap into a quantitative value for specific discrete substitutions. For now, it is suggested that the Improvement Gap is also useful as merely a qualitative observation.[65]

iii. *Time, Efficiency, and Localized Effects*

The disparate capacity for improvement between the Existing Set and the New Set means that future gains in performance favor the New Set. The comparatively greater progress of the New Set technologies then mitigates the need for a separate normative justification for decarbonization: "better" and less expensive technologies generally win regardless of belief structures. It follows that, to the extent the Improvement Gap holds, the technologies of the New Set can be expected to replace the artifacts in the Existing Set over time.

Goals of decarbonization, however, do not require or admit of external temporal measures. Specifically, decarbonization goals are already calibrated to the time in which it has been determined useful to substantially reduce greenhouse gas emissions.[66] A preference for decarbonization is thereby revealed as a simple temporal preference. Helpfully, considerations of general societal efficiency are not accounted by a counting analysis. This is useful in that opinions vary on what should be generally optimized *ex ante*. Restated, an individual might have normative preferences for transitioning from the Existing Set while still trusting that there can be variability in the structures and processes that inhere in the New Set.

More to the point for those whose normative preferences favor reduced greenhouse gas emissions, this blunt technological reductionism counsels strategic action in substitutions out of the Existing Set from the New Set (as discussed later). Likewise, counting reveals that arguments dismissing the impact of local action are technologically unaware (i.e.,

65. Specific support for this view is found in the circumstance that the new technologies underpinning the convergence of the electricity and transport sectors are often shared. For example, lithium-ion battery energy storage is used both for storing generated electricity and electric vehicle propulsion.

66. *See, e.g.*, PATHWAYS, *supra* note 7; *see also* IPCC Special Report, *supra* note 15 (describing time constraints to achieving decarbonization).

decarbonization is a global problem, and the world's atmosphere is shared, therefore individual actions are comparatively unimportant). The reason is again traceable to the Improvement Gap, together with the process of technological change that follows adoption including learning-by-doing at local levels. Transitioning from the Existing Set to the New Set is seen through counting as a series of individual discrete steps each with global impact. Rather than a hypothetical (or fanciful) perspective, this observation comports with existing empirical evidence: the Existing Set itself consists of only a handful of technological artifacts—some combination of coal, oil, gas, internal combustion engines, and steam turbines—that have predominated everywhere in the world.

iv. *Corrective to Continuity and Abstraction Biases*

Consider a counting approach against the White House Council on Environmental Quality proposal to require the considered effects of a proposed action to be "reasonably foreseeable" and require a "reasonably close causal relationship."[67] As counting has shown, the Improvement Gap is foreseeable, provided the problem of decarbonization is properly framed. Elements in the New Set have substantially greater practical and theoretical capacity for performance gains than do the corresponding elements of the Existing Set. Analysis that ignores the effects of discrete changes because they seem inconsequential or lack a "reasonably close causal relationship" thereby unintentionally shorts a known process of technological adoption.[68]

In a similar manner, counting provides a useful corrective to existing continuous analyses overly focused on the effects of emissions rather than discrete technological causes.[69] For example, a counting approach is useful for countering Continuity Bias, the predominant heuristic for present decision-making. Past actions or occurrences are largely not relevant to a counting analysis, except in observing certain technological artifacts being more or less numerous, and the effect such changes promise for further altering existing systems. Prospective or contemporary discrete changes, which are trivial or uninteresting to marginal rate analysis, are treated as

67. *See* WHITE HOUSE COUNCIL ON ENVIRONMENTAL QUALITY PROPOSAL, *supra* note 3.

68. A corollary perhaps is that we should not be overly sure of our ability to quantify severe qualitative risks. *See, e.g.*, Rosen & Guenther, *supra*, note 13 (describing, among other things, cost projection defects in integrated adaptation models that reduce incentive for policymakers to act).

69. One of a handful of exceptions is the pioneering Carbon Tracker Initiative, which is concerned with, for example, the number of coal plants that must be replaced worldwide to meet a decarbonization goal. CARBON TRACKER INITIATIVE, https://perma.cc/Y3M3-9UN9. For a summary review of the development of those conceptual devices, see BEN CALDECOTT ET AL., SMITH SCH. ENTER. UNIV. OXFORD, STRANDED ASSETS AND SCENARIOS (2014), https://perma. cc/7KGM-PE8B.

determinative in a counting approach due to scale and the Improvement Gap.

A discrete perspective further allows a counting approach to avoid Abstraction Bias as no *ex ante* decisions on system efficiency need be assumed. In this way counting illustrates that the purported necessity of, for example, colossal infrastructure programs or carbon taxes or otherwise, are merely expressions of specific normative preferences for how the New Set should evolve. Even for proposals that are misguided, a counting approach is largely unaffected because the process of adoption is itself the proof.[70] A counting approach works whether it is believed that decarbonization goals reflect speculation or are, in reality, vital to species survival. Individuals and communities need not wait for resolution of these differing perspectives to make decisions leading to immediate reductions in greenhouse gas emissions.

Counting is not claimed to always represent a useful methodology. The convergence of factors present in the problem of decarbonization may not be present for other matters of private and public choice. Even in the context of decarbonization, an objection to this reductionist technological view is that individual and public choices may prove insufficiently robust to meet decarbonization goals. For example, the New Set may not improve quickly enough through adoption, or achieve sufficient scale, to cause a change in the fundamental replacement calculus of the Existing Set. Meaning that if the technologies in the New Set are not demonstrably better by non-emissions metrics than the replacement of the Existing Set they might slow, or stall as social values are heterogenous. At this time, that risk appears anti-empirical although its existence ensures continued debate of decarbonization within the larger polity, which is natural and appropriate.

Nonetheless, despite limitations, counting reveals important insights that marginal (and statistical regression) methodologies do not. Foremost, that decarbonization need not solely represent a collective action problem in the U.S. Under a counting analysis, each individual or community decision to replace an element of the Existing Set is a vital step toward quickening the pace of improvement in the New Set and much more. This understanding has specific strategic consequences as the following case study demonstrates. Rather than divisive, it is claimed that the transparency provided by a counting approach is of net benefit in a democratically-controlled, federalist, multi-jurisdictional set of nested regulatory

70. If the Improvement Gap is correct, and past qualitative experience with technological adoption holds, then substitutions will result in decarbonization regardless of heterogenous preferences. An exception is circumstances where individuals and localized preferences are frustrated by law and regulation. *See* David J. Hess, *Sustainability Transitions: A Political Coalition Perspective*, 43 RSCH. POL'Y 278 (2014); *see also* Geels, *supra* note 53.

processes, particularly where broad social consensus and control eludes those that most fervently seek it.

III. Case Study of Counting for an Electric Utility

Electricity procurement sits at the nexus of decarbonization because the electricity and transport sectors are converging and, together, account for most greenhouse gas emissions in the U.S. In most industrialized countries, including the U.S., electricity is still predominantly delivered by and through electric utilities. Any strategic plan for addressing decarbonization is therefore likely to run through, or around, a local electric utility. The following case study explores the contours of decarbonization through an evaluation of one specific utility.

A. A Pernicious Technical Myth about Electricity

Before proceeding, a technical detail should be cleared. Perhaps the most pernicious technical myth about electricity delivery in the U.S. is that the power grids infrastructure is an enormous seamless, synchronous machine, with demand load balanced against supply as electrons seamlessly move throughout the country to where they are needed. This is a powerful, evocative, and fundamentally inaccurate description of domestic electricity procurement. Like many simplified stories, this vision carries elements of truth as supply of electricity must indeed be tightly balanced with load demand and electrons certainly move fast.

One issue amiss in grand visions of a national or even broad regional "integrated" grid is a bit of commonsense: alternate current electricity is not a good long-distance traveler, and in the U.S., nominal operating line losses are between eight percent and fifteen percent.[71] (Direct current transmission and other re-engineered solutions have problems too, chiefly cost and dynamic management.[72]) The problem of line losses worsens depending on various factors, including additional distance and heat. At very long distances, practical voltages cannot overcome line resistance at all, although well before that point, increasing line losses, the need for

71. *See generally*, J.C. MOLBURG ET AL., ARGONNE NAT'L LAB'Y, THE DESIGN, CONSTRUCTION, AND OPERATION OF LONG-DISTANCE HIGH-VOLTAGE ELECTRICITY TRANSMISSION TECHNOLOGIES (2007) [hereinafter MOLBURG]; *see also* BOOTH & ASSOCS., DISTRIBUTION SYSTEM LOSS REDUCTION MANUAL (1983). In countries with less developed infrastructure, the percentage losses may be multiples higher; *see, e.g.*, Michael C. Anumaka, *Analysis of Technical Losses in Electrical Power System (Nigerian 330KV Network as a Case Study)*, 12 INT'L J. RELIABILITY, RISK & SAFETY 320 (2012) (noting transmission losses in the Nigerian grid of up to 40 percent).

72. *See, e.g.*, MOLBURG, *supra* note 71, at 50.

synchronicity between generators, and other factors constrain the economic distance for the transmission of alternating current.[73]

This limitation of alternating current electricity grids highlights an important reality: substituting a single node of electricity consumption results in more pronounced *localized* effects to the surrounding power grid, all other things equal. The conclusion is bolstered by the balkanized physical and operational architecture of the U.S. electricity infrastructure.[74] It is further supported by the observation that centralized electricity networks (unlike communications networks) are not strictly necessary for the procurement of electricity, a conclusion that has been empirically demonstrated.[75]

With that technical understanding in mind a simplified counting analysis of an electric utility can be introduced. The following discussion concerns a governmental-owned utility although the procession of analysis would work the same for any investor-owned electric utility, with reasonable adjustment.

B. Tennessee Valley Authority

The Tennessee Valley Authority ("TVA") is a corporate agency and instrumentality of the U.S. government.[76] It was initially considered a gem in the regulatory crown of the New Deal although its evolution into a government-owned electric utility and comparatively little more may hold

73. Perhaps 300 to 350 miles, subject to various factors, although line losses increase incrementally with distance due to impedance.

74. As one example, the North American electricity system is made up for four grids, or interconnections, West, East, Texas (ERCOT), and Quebec. These interconnections are not synchronized, meaning that the sine waves of alternating current are not in phase, so the grids cannot share electricity, except through limited and few direct current connections.

75. *See* WOODMAC DISTRIBUTED SOLAR REPORT, *supra* note 57. *See generally* Trahan, *Regulating*, *supra* note 13, at 1113, 16–19. Electricity networks do not generate positive networked effects, as additional users do not make the economic good of electricity more valuable to users on the network. For illustration of the concept, contrast electricity with communication technologies: your phone is more valuable if other folks have one too; whether your neighbor is on the power grid or off does not affect the value of the electricity that you consume. The lack of positive networked effects imply that a solely centralized electricity grid is not a technical requirement of electricity procurement. Meanwhile security hazards do exhibit non-linear growth in a centralized electricity delivery system as additional users join the network. Compare Metcalfe's Law, the rubric named for and popularized by Robert Melancton "Bob" Metcalfe, where the value of a telecommunications network is proportional to the square of the number of connected users of the system. Alternately, the community value of a network grows as the square of the number of its users increases. In both instances, the primary value questions are how many users does the network provide access to and interaction with. Such value propositions are inapposite for electricity as a good.

76. *See generally* Tennessee Valley Authority Act of 1933, 16 U.S.C. § 831 (2012).

lessons for New Green Deal proposals.[77] By provision of federal statute TVA has a monopoly in its service area, which covers a population of nearly 10 million over parts of seven states.[78]

i. *Legal Constraints and Board Composition*

Similar to other electric utilities, a primary challenge facing TVA is determining which technologies to select to procure future electricity generation. A requirement in its organic statute, the Tennessee Valley Authority Act, sets parameters on that decision-making process, requiring TVA to:

> . . . employ and implement a planning and selection process for new energy resources which evaluates the full range of existing and incremental resources (including new power supplies, energy conservation and efficiency, and renewable energy resources) in order to provide adequate and reliable service to electric customers of the Tennessee Valley Authority at the lowest system cost.[79]

Assume for present purposes, as TVA does, that this statutory language represents a simple command to provide electricity at the lowest system cost possible.[80] This interpretation is traceable to TVA's anachronistic mission to use federal support to promote economic development in the Tennessee Valley.[81] In essence, the argument is if commerce thrives on energy, then delivering cheap electricity promotes commerce. A key consideration, however, one that was introduced in the discussion of the issue of Continuity Bias, is determining what temporal period should be optimized. In a rapidly changing technological landscape, cheap today does not imply cheap tomorrow. The discussion of the issue of Abstraction Bias meanwhile presages an inquiry of whether TVA is an

77. *See* ERWIN HARGROVE, PRISONERS OF MYTH—LEADERSHIP OF THE TENNESSEE VALLEY AUTHORITY 1933 TO 1990 20–22, 122–125 (1994) [hereinafter HARGROVE] (detailing the original grassroots mission of TVA to bring technological tools to the people, and the resulting evolution into a large power company monopoly). *See generally* PHILIP SELZNICK, TVA AND THE GRASS ROOTS; A STUDY IN THE SOCIOLOGY OF FORMAL ORGANIZATION (1949) [hereinafter SELZNICK].

78. *See* Federal Power Act, 16 U.S.C. § 824k(j) (2012).

79. 16 U.S.C. § 831m–1(b)(1).

80. *See* U.S. SEC. & EXCHANGE COMM'N, TENNESSEE VALLEY AUTHORITY 10-K FILING 11 (2018), https://perma.cc/42HB-39KQ [hereinafter 2018 TVA 10-K]. *See also* U.S. SEC. & EXCHANGE COMM'N, TENNESSEE VALLEY AUTHORITY 10-K FILING 47 (2019), https://perma.cc/65R2-MW9V [hereinafter 2019 TVA 10-K].

81. *Id.* at 21.

effective organizational structure for procuring all or most electricity in the Tennessee Valley.

For now note that TVA has not been adept at meeting its lowest cost mission for residential and small commercial customers.[82] Smaller customers subsidize large industrial users of electricity within the TVA service area, paying electricity rates roughly two to three times higher, a percentage that has been increasing in recent years.[83] That discrepancy in pricing is the prerogative of the TVA Board of Directors, who are provided the sole authority and responsibility for establishing electricity rates under the TVA Act.[84]

ii. *Financial Position*

As an instrumentality of the U.S. government, TVA enjoys the implicit guarantee of the federal government which underpins its AAA credit rating (by Fitch), far higher than for investor-owned U.S. electric utilities.[85] Indeed, TVA acknowledges that its high credit rating would not be warranted without implicit governmental guarantee.[86] Although TVA is subsidized by the federal government in various ways,[87] its capital funding is wholly dependent on private debt placements.[88] Governmental support allows TVA to carry a high degree of financial leverage.[89]

The Governmental Accountability Office ("GAO") had previously found TVA's financial leverage to be of concern in an investigative report

82. *See* Melissa Whited & Tim Woolf, *Electricity Prices in the Tennessee Valley: Are Customers Being Treated Fairly?*, SYNAPSE ENERGY ECON. INC. 1 (Jan. 31, 2018), https://perma.cc/2E75-2SYA.

83. *Id.*

84. 16 U.S.C. § 831a(g)(L) (2012). The Board consists of up to nine members, serving staggered five-year terms; appointment is by the President of the United States with confirmation required by the U.S. Senate. 16 U.S.C. §§ 831a(a)(1), 831a(d).

85. *See Credit Ratings*, TENNESSEE VALLEY AUTHORITY (last visited Sept. 23, 2020, 8:30 AM), https://perma.cc/6MEE-YX9L.

86. *See* 2018 TVA 10-K, *supra* note 80, at 37 ("TVA's current credit ratings are not based solely on its underlying business or financial condition but are based to a large extent on the legislation that defines TVA's business structure [including] . . . TVA's status as a corporate agency and instrumentality of the U.S."); *see also* 2019 TVA 10-K, *supra* note 80, at 37.

87. Among the many benefits is a $150 million credit facility with the United States Department of the Treasury. *See* 2019 TVA 10-K, *supra* note 80, at 110.

88. The cap on private debt placements is $30 billion. *See* 16 U.S.C. § 831n-4(a) (2012); *see also Tennessee Valley Authority, FY 2020 Budget Proposal & Management Agenda and FY 2018 Performance Report*, TENN. VALLEY AUTHORITY 10 (March 18, 2019), https://perma.cc/A2UU-JCAL [hereinafter *2020 TVA Budget*].

89. In its 2020 budget proposal to Congress, TVA reported total financing obligations of $24.3 billion, with billions more in future obligations continuing to accrue. *See id.* at 31.

on its finances delivered in 2017.[90] TVA responded to the report by promising to reduce its debt obligations over several years by increasing consumer electricity rates, limiting the growth of operating expenses, and reducing capital expenditures.[91] TVA thereafter seemingly enjoyed limited success in reducing long-term debt,[92] although its broader financial picture deteriorated. For example, absent from TVA's response to the GAO report was agreement to fund its pension obligations at a higher rate.[93] Compared to typical levels set by large investor-owned utilities, TVA substantially underfunds its pension obligations, a problem that is worsening.[94] Another example is seen in TVA's asset retirement obligations which have grown by a factor of three, approximately $3.6 billion, since 2005.[95]

Electricity sales and financings furnish essentially all of TVA's revenue and are therefore vital for repaying its private bond holders.[96] This circumstance explains TVA's practice of "capacity capture." Capacity capture is a method by which electric utilities overbuild generation capacity and infrastructure for future demand and then charge those investments to consumers over time through incremental increases in electricity prices.[97]

90. U. S. GOV'T. ACCOUNTABILITY OFF., TENNESSEE VALLEY AUTHORITY: ACTIONS NEEDED TO BETTER COMMUNICATE DEBT REDUCTION PLANS AND ADDRESS BILLIONS IN UNFUNDED PENSION LIABILITIES (Mar. 2017), https://per ma.cc/QM4F-GUCE [hereinafter GAO Report].

91. *Id.* at 1.

92. Long-term debt was reduced by about 4% from the end of fiscal-year 2016 to the end of fiscal-year 2018.

93. *See* GAO Report, *supra* note 90, at 1; *see* 2019 TVA 10-K, *supra* note 80, at 66; *see also* 2018 TVA 10-K, *supra* note 80, at 125–28.

94. Typical investor-owned utilities fund pension obligations at a rate of between 85 percent and over 100 percent. *See, e.g.,* CHRISTOPHER MUIR AND SHANG YANG CHUAH, CFRA (S&P GLOBAL), INDUSTRY SURVEYS, ELECTRIC UTILITIES at 26 (Aug. 2018); TVA's funding rate of fifty-nine percent as of the end of fiscal-year 2019 implies a funding gap of approximately $3.3 billion to reach the low-end of electric utility industry standards (the gap increased from $2 billion in 2018). *See* 2019 TVA 10-K, *supra* note 80, at 66. *See also* 2018 TVA 10-K, *supra* note 80, at 37, 125.

95. *See* U.S. SEC. & EXCHANGE COMM'N, TENNESSEE VALLEY AUTHORITY 10-K FILINGS 2005–2019. (Estimates of future obligations necessary to retire, primarily, power plants from service. At present, approximately $5.453 billion compared to $1.8 billion in 2005, and not yet reflected in TVA's total financing obligations.) *See* 2019 TVA 10-K, *supra* note 80, at 151; 2006 TVA 10-K at 140 (the 2005 10-K was not immediately available, although the 2006 10-K provides prior year information).

96. 2019 TVA 10-K, *supra* note 80, at 8.

97. Capacity capture relies on a cost recovery mechanism known as "rate basing," a term which I tried to avoid so as not to confuse the other discussion of rates. Assets are overbuilt due to construction time constraints and other practical factors and, today, to preclude competition. Due to the progress of technological substitutes, it is suggested that the concept of capacity capture is distinct from the Averch–Johnson effect, which postulates that the reduced cost of capital available to regulated utilities will incentivize utilities to over-accumulate and over-deploy capital as subsidizing risk interferes with profit-

There are sensible historical reasons, technical and otherwise, for financing huge single-asset capital expenditures in a similar way, although a modern effect of capacity capture is to foreclose competition from New Set technologies. Consumers ultimately hold the risk of capital deployed for new generation assets and, once financially leveraged, are linked to a specific technological pathway; a similar and stronger analysis applies to delivery modalities.

iii. *Emissions*

TVA reports that it produces more than one out of every 100 pounds of carbon dioxide emitted in the U.S. from all sources, ~ 52 million metric tons annually.[98] An independent count observes that TVA substantially undercounts its carbon dioxide emissions by around 10 percent, or 5 million metric tons annually.[99] In step with other electric utilities, TVA focuses on rates of emissions efficiency and reports an annual average figure. For example, in 2018 TVA reported an emissions rate of 825.09 pounds of carbon dioxide per megawatt hour of generation measured over the timescale of a calendar year.[100]

A marginal analysis, by contrast, would measure change at the margin of the relationship between emissions and generation at a past instant or forecast the same for a future instant, e.g., incremental generation deployed to meet demand. A marginal *rate* of emissions is the pace at which such

maximizing decisions to seek equality between the marginal product of the inputs and the ratio of costs. *See* Harvey Averch & Leland Johnson, *Behavior of the Firm Under Regulatory Constraint*, 52 AM. ECON. REV. 1052 (1962).

98. Total U.S. carbon dioxide emissions are calculated at around 5.1 billion metric tons. *See, e.g.*, *U.S. Energy-Related CO2 Emissions Increased in 2018 but Will Likely Fall in 2019 and 2020*, U.S. ENERGY INFO. ADMIN.: TODAY IN ENERGY (Jan. 28, 2019), https://perma.cc/2GF2-DDWN. *Compare* EUR. COMM'N, JOINT RES. CTR., FOSSIL CO2 EMISSIONS OF ALL WORLD COUNTRIES (2018), https://perma.cc/D624-CSTK. For an explanation of land sinks in the determination, *see* ENVTL. PROTECTION AGENCY, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS 1990-2017 (Apr. 11, 2019), https://perma.cc/3A6X-6L3T. Using TVA's reported emissions for 2018 yields, 52,252,375/~5,100,000,000 = 1.02 percent. Properly counted, TVA's emissions are higher, *see infra*, note 107.

99. *See Form EIA-923 Detailed Data*, U.S. ENERGY INFO. ADMIN. (2018) [hereinafter EIA 2018].

100. *See*, *Carbon Dioxide*, TENN. VALLEY AUTHORITY (last visited Sept. 23, 2020, 9:33 AM), https://perma.cc/37LC-QR2Z [hereinafter TVA CO2 Report].

changes occur, are expected to occur.[101] As discussed, Continuity Bias in marginal rate analysis reflects an assumption that the underlying relationships, here generation and emissions, are reasonably stable—not constant necessarily, just staying on the curve. Employing a rate calculation, average or marginal, is then a comprehensible effort to tie electric generation output together with emissions, to provide a measure of the efficiency with which electrical generation is produced over some temporal period. Such metrics are easily recognized and inhered to adjust for the size of disparate generation portfolios, giving the appearance of consistency.

For legacy electric utilities a rate of emissions offers optical benefits. TVA, for example, ranks among the leading global emitters of carbon dioxide over its eighty-five-year history. Focusing on a rate of emissions avoids discussion of sunk costs—and normative entanglements—concerning proportionate shares of historic and modern world carbon stocks. A further justification for viewing emissions from a rate perspective is that electricity generation is generally viewed favorably and desired to continue into the future, unlike an activity that may have been deemed to have no material social benefit, e.g., tobacco.[102]

Yet, the earth's atmosphere is largely a closed and finite system, thus emissions performance goals are net measurements of magnitude due to cumulative impact. As described in the discussion of the issue of Abstraction Bias, dividing the amount of bad (emissions) by good (generation) is a fundamentally flawed metric of electric utility performance. Adjusting that average rate would require incremental (marginal) change in TVA's emissions or its generation, as those variables relate to one another. Such metrics would not directly measure energy conservation or efficiency, or alternate approaches to electricity procurement—e.g., distributed generation or storage—that do not

101. It is a concern du jour that policy decisions regarding decarbonization might be made by relying on measurements of average carbon emissions, e.g., the amount of carbon emitted over some time period for a portfolio of electricity power plants. As one example, the Rocky Mountain Institute recently produced a primer cautioning commentators against relying on average rates of emissions noting that such metrics fail to account for change at the margin, the incremental adjustment from existing conditions. *See On the Importance of Marginal Emissions Factors for Policy Analysis*, ROCKY MOUNTAIN INST. (WITH WATTTIME) (2018), https://per ma.cc/K7GY-32Z5. This is a useful reminder; however, it carries special methodological danger in times of abrupt technological change and is susceptible to assumptions of the social purpose for which it is applied.

102. Coincidentally, recent investment commentary has explicitly compared the use of fossil fuels to tobacco. *See, e.g.*, *Jim Cramer, Mad Money* (CNBC television broadcast Jan. 31, 2020), https://perma.cc/46MD-GKMB (stating that a trend of divestment of stock shares of oil and gas companies is a "death knell" reflecting the sentiment that these companies "are the new tobacco").

presuppose that TVA is necessary to electricity procurement. In brief: differential rates cannot measure what is not there.

Applying a performance metric to TVA's *aggregate* emissions is instead necessary to contextualize its performance. A science-based aggregate measure from the Deep Decarbonization Pathways ("DDP") is applied here for familiarity.[103] Per this DDP standard, emitters need to reduce carbon dioxide emissions by eighty percent prior to 2050, measured from a base year of 1990, to limit certain projected catastrophic effects of climate change (80/2050 Goal).[104]

For the calendar year 1990, TVA reported consumption of electricity prime movers (coal, gas, diesel fuels) implying carbon dioxide emissions of approximately 84 million tons.[105] In order to achieve the 80/2050 Goal, TVA then needs to reduce its annual carbon dioxide emissions by 67 million tons, or an emissions ceiling of around 17 million tons annually by 2050.[106] If it emits more, it fails the target.[107] This is separate explanation for the limited usefulness of differential efficiency rates, average or marginal in this context: irrespective of whether the rate is 825lbs/MWh per some time scale, half that, or any non-zero number, such rates are only relatable to goals of magnitude if integrated with consumption.[108] The guiding principle of integration is relevant here as it does not matter how fast you hit the wall if hitting the wall will kill you.

Not all electric utilities undercount carbon dioxide emissions, but it is frequent practice to omit additional analytic steps that would tie rates of emissions to consumption and net performance standards. This undermines policymakers' ability to make basic assessments, e.g., whether an electric

103. PATHWAYS, *supra* note 7, at 5.

104. *Id*.

105. *Historic Form EIA-906 Detailed Data with Previous Form Data (EIA-759)*, U.S. ENERGY INFO. ADMIN. (1990). TVA itself does not provide an emissions estimate for 1990, its provided calculations only go back to 1995. *See* TVA CO2 Report, *supra* note 101. Annual data sets from four, post-1994 years were sampled with the same methodology and the differences between the results and TVA's reporting varied by up to a maximum of less than two percent. Only power plants that TVA owned were used for this purpose, *but see supra* note 100.

106. Eighty percent and twenty percent, respectively, of eighty-four million.

107. This would likely be viewed as overconservative for ignoring time value of emissions, not accounting for future Scope 2 emissions reclassification, and providing no margin or bulwark for unexpected outcomes. *See generally* Rosen & Guenther, *supra* note 13.

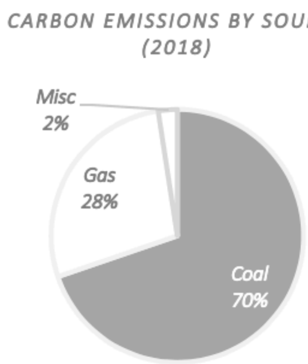
108. The mathematical processes can be reversed of course but the immediate point is that, in practice, electric utilities do not do so. As discussed, even a practice of integration leads to confused analysis when applied to the avoidance of consumption via energy efficiency and other variables situated outside its division.

utility's improved emissions performance is adequate.[109] Obtaining satisfactory information may depend on fixing data misconstructions and analytical omissions, an informational role that might be immediately filled by a private institution.[110]

iv. *The Substitution of Twenty-Two Fossil Fuel Sites*

Existing Set—Generally

TVA serves a nearly ten-million person service-area and produces more than one out of every 100 pounds of carbon dioxide emissions in the U.S., yet it only owns twenty-three fossil fuel sites (with many locations having multiple generating units, Kingston Fossil Plant, for example, has nine).[111] TVA is expected to retire one of its five remaining coal plants (Bull Run), with decommissioning planned for December 2023, leaving twenty-two fossil fuel sites without assigned retirement dates. This is TVA's Existing Set.[112]



	2018 Attributable Annual Emissions	80/2050 Goal Annual Emissions
Coal	~ 36.455 mm tons	0 mm tons
Natural Gas	~ 14.522 mm tons	15.726 mm tons
Miscellaneous	~ 1.274 mm tons	1.274 mm tons
TOTAL	~ 52.25 mm tons	17 mm tons

Table 1

Figure 2: Carbon Emissions by Source in 2018

109. Historic emissions reductions at TVA, for example, are largely attributable to decreases in consumption from, e.g., the adoption of LED lightbulbs, along with the substitution of natural gas generation for coal, along with increased nuclear generation.

110. Establishing a third-party database, inclusive of each individual electric utility and their respective plants, could integrate consumption and provide a view of its likely future trajectory, the latter of which would be fixed to the end date of an emissions framework, like the DDP. The projection of growth—the increase in the independent variable of future consumption—could further be bracketed within reasonable bounds or subjected to multiple case analysis. Such an approach is especially appropriate in the special case of electricity as it is, as a good, regulated toward universal access at a socially acceptable price.

111. *See* EIA 2018, *supra* note 99.

112. *Id.*

A coincident and well-known technological story is that coal, as a prime mover of electricity generation, is today grossly uneconomic in the U.S., even without the existence of a carbon tax. Ignoring production methane releases, natural gas is much cleaner than coal, emitting roughly forty-three percent fewer pounds of carbon dioxide than bituminous coal, per equivalent British thermal unit. As such, it is reasonable to ask how much natural gas production could persist concurrent with TVA achieving the 80/2050 Goal for annual emissions?

	2018 Annual Generation	*80/2050 Goal Annual Emissions Cap*	*Equivalent Natural Gas Generation*	*80/2050 Goal Additional Available Capacity*
Natural Gas	~ 36 TWh	15.726 million tons	~ 39 TWh	~ 3 TWh

Table 1: Natural Gas and Annual Generation in 2018

Table 1 shows that—assuming all other fossil fuel generation of TVA is retired—no more than three TWh of additional new natural gas generation could be brought into the TVA system and still meet the 80/2050 Goal.[113] In 2018, coal generation accounted for approximately thirty TWh of electricity in the TVA system. This means that approximately ninety percent of existing coal-powered generation cannot be substituted with natural gas. The noteworthy corollary is that even a very lax emissions reduction goal could not result in a majority replacement of coal generation with natural gas.

The foregoing provides specific illustration of the issue of Continuity Bias in analyses that recommend the replacement of coal with natural gas due to the marginal improvement in emissions performance. Specifically, substantial incremental substitutions of natural gas for coal would consistently signal efficiency improvements, yet such substitutions would simultaneously ingrain a technological pathway that ensures failure to reach the 80/2050 Goal. The misconstruction of efficiency here carries extra meaning as TVA has stated that the capacity of its generating portfolio is sufficient to meet demand for the next few years without capital expenditures on new power plants.[114] As such, there is a lull in the

113. There are a number of ways to obtain the product, all which yield the same result. For quick simplicity, assume that the rate of carbon dioxide emissions per GWh of natural gas generation is the same as it was in 2018, roughly .4035 carbon dioxide metric tons/GWh. Applying that rate to thirty-nine terawatt hours would thereby result in a product of roughly 15.726 million metric tons of carbon dioxide emissions. *See* 2019 TVA 10-K, *supra* note 81; EIA 2018, *supra* note 100.

114. *See* 2018 TVA 10-K, *supra* note 87, at 61. *See also Integrated Resource Plan: Volume I Final Resource Plan*, TENN. VALLEY AUTHORITY 4-11–4-13 (2019),

deployment of new generation. The minimal additional consumption available to be met by natural gas is therefore tied to coal plant retirements in the interim, regardless of emissions.[115] This simplified picture does not account for, among other things, financial considerations in deploying additional natural gas generation which increase the risk of any further plant construction.[116] The foregoing has, in sum, defined TVA's Existing Set within the parameters of 80/2050 Goal; prior to 2050, TVA must: (i) retire all of its coal power plants; (ii) replace no more than approximately ten percent of coal generation with natural gas; and (iii) approximately ninety percent of existing coal plant generation must be replaced with technologies from the New Set, which does not include natural gas.

Note that this analysis omits consumption growth. Even an assumption of nominal growth carries material impact. Recent EIA projections forecast an approximate one percent growth rate for electricity consumption in the TVA service area.[117] Even substantially rounding down that forecast to an annual increase of 0.75 percent implies a need for more than thirty-eight TWh of additional generation by the year 2050 as compared to 2018, or more than current generation from either coal or natural gas.[118] Further delimiting the above 80/2050 solution for TVA, all

https://perma.cc/TX23-EL93 [hereinafter 2019 TVA IRP]. TVA spends roughly two hundred million per year in scattered capacity investments, but this is an order of magnitude (plus a few times) lower than a major new generation investment in, e.g., a new nuclear reactor.

115. This ignores the problem of time value of emissions and does not account for the necessity of continued reductions after 2050.

116. Natural gas power plants historically require a minimum twenty-five-year operating schedule to recoup initial investment at a rate of return justifying investment risk. *See, e.g., GE Cautionary Tale*, *supra* note 121, at 6. A natural gas plant completed before 2024 may fully amortize, even including a twelve-month decommission allowance, but after 2026 the standard amortization schedule is cut short. If a natural gas plant cannot continue to economically operate past 2050 there is a mismatch between operating life and the schedule of amortizing debt payments. For example, losing one year of a twenty-five-year amortization schedule represents only a four percent change in time duration. But by 2030, five years of amortization would have been lost, a twenty percent change in duration, resulting in significantly higher service payments, a similar cost effect to substituting thirty, twenty, and fifteen-year mortgage terms, although the operational risks of the power plant in an emissions-reduction regulatory environment are just one of many problematic variables.

117. *Annual Energy Outlook 2019, with Projections to 2050*, U.S. ENERGY INFO. ADMIN. (Jan. 24, 2019), https://perma.cc/JA3T-LP9B. The EIA reference case assumptions on electric car adoption already are in need of considerable upward revision. It should be generally noted that electricity demand growth forecasts, from the EIA and others, have not been particularly accurate in the past. *See, e.g.*, Michael Wara et al., *Peak Electricity and the Clean Power Plan*, 4 Electr. J. 1 (2015), https://perma.cc/AQU4-HL4A.

118. In 2018, TVA-owned plants generated approximately 143 TWh of electricity generation. Applying a nominal three-quarters annual increase in demand results in consumption growing by over thirty percent to 2050.

future consumption growth in would need to be met by technologies from the New Set.

(1) Existing Set—Individual Artifacts

A counting analysis describes the correspondence between the Existing Set and the New Set at the set level and also at the level of individual technological artifacts. The above discussion delimits the set level correspondence between the technologies of the Existing Set (coal, diesel, and natural gas) and those in the New Set (solar, wind, battery energy storage, energy efficiency or conservation). The next step is to evaluate an individual technological artifact. By way of example, the following table lists six of TVA's largest fossil power plants, ranked by aggregate generation.[119]

#	Power Plant Name Year of Commission Physical Address	Primary Mover	Carbon Dioxide Emissions in tons (2018)	Net Generation & Coal Fuel Consumption (2018)	Approximate Distance From Major Population Centers
1.	Cumberland (1973) 815 Cumberland City Rd, Cumberland City, TN 37050	Coal (total) - Bituminous - Refined	10,406,612 tons	10,370,388 MWh - 1,100,781 short tons - 3,393,060 short tons	14 miles to Clarksville (153K) 40 miles to Nashville (689K) 147 miles to Memphis (652K)
2.	Shawnee (1953) 7900 Metropolis Lake Rd, West Paducah, KY 42086	Coal - Subbituminous	8,483,647 tons	6,276,370 MWh - 4,029,801 short tons	9 miles to Paducah (25K) 75 miles to Fort Campbell (250K) 85 miles to Clarksville (153K) 120 miles to Nashville (689K)
3.	Paradise (2017) 13246 KY-176, Drakesboro, KY 42337	Natural Gas	2,200,130 tons	5,879,656 MWh Combined cycle: Steam 14,254,382 MWh Combustion 27,115,578 MWh	35 miles to Bowling Green (67K) 75 miles to Nashville (689K)
4.	Magnolia (2003) 352 MS-4, Ashland, MS 38603	Natural Gas	2,072,475 tons	5,554,670 MWh Combined cycle: Steam 15,127,668 MWh Combustion 23,841,940 MWh	31 miles to Memphis (652K)
5.	Gallatin (1956 to 1959) 1499 Steam Plant Rd, Gallatin, TN 37066	Coal - Subbituminous	6,834,292 tons	5,127,319 MWh - 3,246,344 short tons	4 miles to Gallatin (37K) 10 miles to Lebanon (32K) 19 miles to Nashville (689K)
6.	John Sevier (2012) TVA Rd, Rogersville, TN 37857	Natural Gas	1,812,738 tons	4,786,949 MWh Combined cycle: Steam 12,284,466 MWh Combustion 21,801,210 MWh	20 miles to Johnson City (66K) 55 miles to Knoxville (187K)
	TOTAL CARBON DIOXIDE EMISSIONS FROM TOP 6 GENERATING PLANTS		31,809,894 tons		
	TVA EMISSIONS TOTAL (2018)		52,252,375 tons		
	TOP 6 PLANTS AS PERCENTAGE OF TOTAL		61%		
	INCLUDING SOON-TO-BE RETIRED BULL RUN AND PARADISE		82%		

Table 2: TVA's Largest Fossil Power Plants

119. *See* EIA 2018, *supra* note 99.

Consider the sixth largest fossil plant by net generation, John Sevier. In 2018, the John Sevier plant generated approximately 4.786 TWh of electricity, with generation split approximately 1/3 steam and 2/3 combustion.[120] For purposes of illustration, assume for now that John Sevier uses all of its generation to supply residential homes, rather than the supply of some amount of industrial steam. For purposes of simplicity, further stipulate that a single residential home consumes 12,000 kWh of electricity per year. John Sevier could thus supply 391,667 homes.

Which homes? Specifically, in evaluating the New Set options for substitution which homes might obtain electricity from a new technology if the desire were to replace John Sevier? The John Sevier plant is located in the Eastern part of Tennessee, approximately 400 miles from Memphis.

As such, decarbonization actions taken by Memphians are not likely to directly impact the operation of the plant.[121] John Sevier instead delivers its power at more economic distances, primarily to the nearby towns of Johnson City, Knoxville, the Oak Ridge Facility, and perhaps, as a supplement, to the cities of Chattanooga and Nashville.[122] Memphians have power plants of their own, of course, including the Allen Fossil Plant, which is located in Memphis, 7 miles from Graceland.[123]

To introduce further necessary detail, the activities of power generation, transmission, and distribution in the U.S. are often handled by different entities. Except for fifty-two industrial customers and six federal installations,[124] TVA does not deliver power directly to customers and instead relies on contracts with 154 municipal and cooperative distributers of electricity.[125] As such, substitutions from the Existing Set in Johnson City and Knoxville would result in more pronounced impacts to the performance of John Sevier and also the local power company (Knoxville Utilities Board) that distributes electricity generated by TVA.

Reducing the performance of John Sevier is an economic problem for TVA, but a potential boon to Knoxville Utilities Board as many residential customers are likely to continue paying for access to the distribution grid (back up energy) regardless of the presence of, e.g., rooftop solar. This divergence provides partial explanation for current calls for municipalities

120. *See* EIA 2018, *supra* note 99.
121. *See* discussion *supra* Part III.A.
122. *See* discussion *supra* Part III.A.
123. *See* EIA 2018, *supra* note 99.
124. These direct customers compromise roughly eight percent of TVA's revenues. *See* TENNESSEE VALLEY INDUSTRIAL COMMITTEE, https://perma.cc/ 6LV7-PARK (last visited Oct. 2, 2020); *see also Public Power for the Valley*, TENN. VALLEY AUTHORITY, https://perma.cc/ST4A-2S6U (last visited Sept. 23, 2020, 2:13 PM).
125. *See* 2019 TVA 10-K, *supra* 80, at 16.

and cooperatives to defect from the TVA system to realize the economic and environmental benefits of technological progress.[126]

This circumstance also provides reasoned explanation for the economic incentive for corporate renewable purchases: quasi-defecting from a legacy electric system while retaining the benefits of the system through private long-term contract.[127] The recent trend of decreased prices for rooftop solar, or at another level, the phase out of natural gas peaker plants in favor of battery energy storage deployments, are examples of technological system risk.[128] TVA well understands the risk of defection as noted in its latest 10-K filing:

> TVA also faces competition in the form of emerging technologies. Improvements in energy efficiency technologies, smart technologies, and energy storage technologies may reduce the demand for centrally provided power. The growing interest by customers in generating their own power through [distributed generation] has the potential to lead to a reduction in the load served by TVA as well as cause TVA to re-evaluate how it operates the overall grid system to continue to provide highly reliable power at affordable rates.[129]

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126. *See, e.g.*, Jurgen Weiss et al., *Power to Memphis: Options for a Reliable, Affordable, and Greener Future*, BRATTLE GROUP 16 (Jan. 2019), https://perm a.cc/NHV2-4VB8 [hereinafter BRATTLE, *Memphis Defection*] (suggesting that Memphis Light, Gas & Water, a local power company that contracts for wholesale electricity from TVA, should exit the TVA system to save $240 to $333 million per year on electricity costs).

127. A corporate data center would not actually defect, of course, as those facilities no more run on the renewable generation power plants that are constructed at their behest than do smelters. Rather, the corporate renewable buyer would obtain access to an entire, balanced electricity system while locking in favorable long-term electricity rates through private contracting.

128. As a somewhat ironic callback to the *GE Cautionary Tale*, *supra* note 121, *see* Charles Newbery, *Energy Storage Poses a Growing Threat to Peaker Plants*, TRANSFORM (Oct. 1, 2018), https://perma.cc/P4ZM-X9T6. As a specific example, *see also* CAL. ST. PUB. UTIL. COMM'N., RESOLUTION E-4949 (Nov. 8, 2018), https://perma.cc/V7YL-PEW7 (approving the replacement of three natural gas peaker plants with battery energy storage).

129. 2019 TVA 10-K, *supra* note 80, at 20. TVA first acknowledged the risk of customer defection due to distributed technologies in its 2018 10-K. *See* U.S. SEC. & EXCHANGE COMM'N, TENNESSEE VALLEY AUTHORITY 10-K FILING 2013–2018. In its 2011 and 2012 10-K filings, TVA warned its creditors that energy efficiency programs might experience insufficient adoption. As a new nuclear reactor, Watts Bar II, came closer to being brought online those warnings turned opposite, and began describing efficiency programs as a threat. Either set of warnings reflect an incongruency between standard corporate concerns and social outcomes.

TVA's acknowledgment that emerging technologies are a threat, rather than a benefit, to its "business" is informative.[130] By evaluating the individual elements of the Existing Set a counting analysis highlights that defections in Knoxville and Johnson City are indeed a problem for TVA generally, but more specifically problematic for the performance (and amortization) of the John Sevier plant. This is a localized effect of a decarbonization action.

TVA has a carbon footprint representing one out of every 100 pounds of carbon dioxide emissions in the U.S. from all sources.[131] It is challenged by financial constraints, including debt load, an underfunded pension account, and growing asset retirement obligations.[132] Despite federal subsidies, TVA's financial position is ultimately dependent on private bond-holders who supply debt for operations and investment.[133] Further, virtually all of TVA's revenues result from electricity sales—which, coupled with its practice of capacity capture, put it in conflict with energy efficiency and conservation, distributed generation, and other "emerging technologies."[134]

Exacerbating the problem, TVA's organizational structure and power system (Existing Set) are geared to legacy assets that are not susceptible to material improvements in practical or theoretical efficiency.[135] This circumstance is among the reasons that calls have become more frequent for municipal and cooperative distributers to defect from the TVA system so as to save money by deploying newer, cleaner, more cost-resilient replacement sources of electricity generation.[136]

130. This highlights a disconnect between electric utility optimization and social benefit analysis. The divergence is even more clearly seen by contrasting TVA's creditor disclosures with the messaging it provides the general public, viz. in its Integrated Resource Plan planning process that details future plans for electricity procurement and generation. The Integrated Resource Plan contradictorily claims TVA's strong commitment to conservation and energy efficiency, and to distributed renewable generation. *See* 2019 TVA IRP, *supra* note 114, at 4–13. Energy efficiency and conservation programs have the effect of reducing the sale of kilowatt hours, i.e., reducing vital revenues, as do distributed electricity procurement technologies, which may imperil TVA's debt repayments.

131. *See* Paul A. David, *Path Dependence, Its Critics and the Quest for "Historical Economics"*, ALL SOULS COLLEGE, OXFORD AND STANFORD UNIVERSITY, WORKING PAPER (2000).

132. *See 2020 TVA Budget*, *supra* note 88.

133. *Id.*

134. *See* 2019 TVA 10-K, *supra* note 80.

135. *See* discussion *supra* Part III.B.ii.

136. *See* BRATTLE, *Memphis Defection*, *supra* note 126.

(2) New Set, Improvement Gap

The next step of analysis is to gauge the strategic effect of a discrete substitution out of the Existing Set from the New Set. Here, this is necessarily a generalized exercise as a detailed counting analysis is well beyond the scope of this article. Instead, the following highlights certain general touchstones of a counting approach.

As discussed, a counting analysis is the expression of a normative preference for decarbonization. Here, it might present as an individual or community preference for fewer greenhouse gas emissions, sooner. Such a preference diverges in material respects from TVA's expressed institutional predilections, and it is likely to differ from the preferences of many other individuals in the Tennessee Valley. TVA is a monopoly and social consensus has proven difficult to reach; what actions can be taken?

First, consider what a counting analysis avoids. Counting circumvents arguments flowing from the issue of Continuity Bias as it is necessarily forward-looking. In the context of TVA, this aspect of a counting analysis recognizes that marginal improvements in emissions efficiency metrics do not represent progress toward goals of decarbonization and instead augur failure.

For example, TVA contends that natural gas deployments in substitute of coal generation are a sound method of energy transition due to the relatively cleaner emissions profile of natural gas. A counting analysis reveals that material deployments of natural gas will lock-in a level of greenhouse gas emissions incompatible with goals of decarbonization.

Counting further avoids arguments of system efficiency inherent in Abstraction Bias. An approach based on counting does not assume *ex ante* that TVA is a necessary or useful organization structure for managing all or most of the technologies in the New Set. It is further not accepted on faith that the specific correspondence of non-injective substitutions between the Existing Set and New Set are known in advance. This aspect of a counting analysis highlights the power of individual choice, community action, and other discrete directed actions.

Meanwhile a counting approach provides a framework to qualitatively describe the Improvement Gap (and, perhaps, quantitatively too). The value of that observation is in identifying that the long-term trend of technological progress is away from the Existing Set and to the New Set. Thus, most normative questions of decarbonization are revealed as temporal—not if such transitions will occur but when will such transitions occur.

What constructive analysis can counting provide? A counting analysis initially confirms, in stark terms, actions an individual in the Tennessee Valley with a preference for (and means to) reducing greenhouse gas emissions should take; chiefly, purchasing elements from the New Set, including distributed renewable generation and an electric car. The electric car purchase is bijective with the subset of internal combustion engine passenger vehicles, while the purchase of distributed renewable generation corresponds, but is non-injective with, the power plants owned by TVA. Stated differently: an electric car is the only practical substitute from the Existing Set to the New Set for that technological artifact, more so in this context,[137] while there are numerous permutations for replacing energy generation in the Existing Set. Note that the purchase of a hybrid-electric car is shown by a counting analysis to be an ineffective decarbonization action because it cannot constitute an element of the New Set.[138]

Assuming a purchase of distributed renewable generation, whether rooftop or community based, did occur, counting would describe how it realizes the Improvement Gap on at least two separate levels. At the global level, improvement in the selected technologies might result in manufacturing scale, supply chain efficiencies, increased investment in research and development and other factors that have been experienced. (This known qualitative observation may, again, be responsive to quantitative measurement).[139] At the local level, cost declines in the New Set substitutes are more likely traceable to gains in learning-by-doing as, for example, new installers conducting repeat installations achieve improvements in community performance. This is a particularly ripe area

137. By way of example, the Tennessee Valley has a high rate of single car ownership and compared with many more urban environments, a lower incidence of public transportation by train. Again, a central purpose of a counting element is to consider substitutions from the Existing Set in a discrete, rather than abstracted manner. Local conditions and decisions are therefore determinative, even for globalized effects resulting from the Improvement Gap being realized by adoption.

138. The design, manufacture, and characteristics of electric drivetrains are fundamentally different in a hybrid internal combustion engine vehicle, therefore belying a claim that the Improvement Gap could be backed into by a hybrid-electric vehicle. As one of hundreds of examples, true electric cars do not require an engineered solution to two large, separated masses that dictate the design of internal combustion vehicles, i.e., fuel tank and engine block. *See Taking the High Road: Strategies for a Fair EV Future*, UAW RES. DEP'T 10–12 (Spring 2019), https://perma.cc/E3V8-MVAM (highlighting important labor concerns in summarizing research showing that 80 percent fewer parts are required in an electric vehicle drivetrain (skateboard layout), and that capital investments may be reduced by half; hybrid-electric cars, by contrast, require more complexity and an even greater number of parts than an internal combustion engine vehicle). *See also* Fred Lambert, *Toyota Produces Shameful Anti-Electric Vehicle Ad to Sell Corolla Hybrid*, ELECTREK (Feb. 12, 2019, 2:50 PM), https://perma.cc/J63X-AB4F. *Compare* Fred Lambert, *Toyota's 'Self-Charging Hybrid' Ad Is Banned in Norway, Deemed a Lie*, ELECTREK (Jan. 24, 2020, 9:34 AM), https://perma.cc/78Z6-THXT.

139. *See DRD Study*, *supra* note 33, at 1. A quantitative measure of dynamic change is related to a question the authors of the renewable portfolio standards surfaced. It is likely a heavy lift for marginal and regressive tools hindered by a dependence on historical data. Instead, if localized actions can be shown to correspond to impacts on specific production curves then perhaps a rough contemporary coefficient might be described for certain cost factors, which could thereafter be generalized.

as soft costs constitute the largest percentage of total costs for renewable generation systems.[140]

For a less obvious effect, consider the localized discrete action and the resulting consequences. Assume that the number of individuals in the Tennessee Valley who wish to take actions to reduce greenhouse gas emissions are scattered geographically. Coalition-building literature discusses the manner and methods that such individuals might cooperate. A counting analysis meanwhile can uniquely inform the strategic ends of such action. For example, a counting approach observes that the John Sevier plant serves, primarily, Eastern Tennessee and mostly does not serve Central and Western Tennessee. It considers that the local power company that contracts for power from TVA, the Knoxville Utilities Board (~ 400,000 customers), is likely to be served in large part by the John Sevier plant. It observes that targeted deployment of distributed renewable generation in, for example, Johnson City, would especially impact the operation of John Sevier (more generally, it would also reduce TVA's electricity sales and revenue along with it).

In this way, counting can be useful in evaluating the number of discrete substitutions necessary to be made from the New Set to move away from any specific element in the Existing Set. Targeted defections in Knoxville and Johnson City would affect John Sevier and, as the sixth largest power plant by generation, reverberate throughout the TVA system. Meanwhile, TVA is highly leveraged in its finances. The review of TVA's financial position indicates that a reduction in revenue of even a few percent is likely to prove problematic for meeting existing debt obligations—companies typically do not elect to grossly underfund pension obligations due to a surplus of operating income. Counting thereby reveals specific ways that an electric utility's position can be made responsive to specific individual and community preferences. Said differently, a counting approach provides an analytical basis for taking strategic action to reduce emissions of greenhouse gases by effectively targeting discrete elements of the Existing Set.

Counting is not claimed as an analytical panacea. Even a granular review of a counting approach would not address related normative concerns. In counting there is no efficiency lodestar or other pat positivist answer to determine the right way forward, although the Improvement Gap does provide a consideration. Rather, a counting approach starts from an articulated preference of what ought to be and traces that line back through

140. *See supra* text accompanying note 43.

a realistic representation of what is, helping to reveal what needs to be done for those that prefer it.[141]

iv. *A Brief Note on TVA's Problem with Nuclear Power*

Nuclear power, never an energy program driven by private economic interest, regrettably remains severely uneconomic in 2020.[156] The soft market for nuclear plants, domestically and internationally, reflects a long track record of nuclear projects substantially underperforming pro forma financial projections, punctuated by periodic economic and social catastrophe.[157] Yet, nuclear power is central to understanding TVA. In late 2016, TVA became the first utility in the U.S. in twenty years to generate electricity from a new reactor, Watts Bar Unit II. The utility before it: TVA.[158] In fact, the TVA generation portfolio features a uniquely high percentage of nuclear power, thirty-nine percent,[159] in part reflecting its history as a one-time instrument of the Atomic Energy Commission.[160]

TVA's experience with Watts Bar Unit II provides another point of disheartening nuclear generation data: it took over forty years from the start of construction of the reactor to commence electricity generation.[161] The final cost, approximately $6.1 billion, compares with an initial budget projection of around $450 million.[162] At present, Watts Bar Unit II remains underutilized, running at a net capacity factor of only 80.9 percent in 2019, whereas the TVA reactor fleet average is closer to ninety percent.

Eventually Watts Bar Unit II will run closer to or above the fleet average, which partially explains why TVA does not anticipate needing new generation for the next few years.[163] Nonetheless, its reactor license runs only for another thirty-five years, so even a couple of years of reduced generation carries potentially meaningful financial consequences, more so considering the initial high fixed costs. In fact, more than half of the nuclear generation in TVA's portfolio is coming off license between the years 2033 and 2036, while seven out of eight reactors are off license by 2041.[164]

Coming "off-license" is not a synonym for retirement, although it does imply a need for substantial capital investments. The materials science underpinning nuclear reactor technology, like all generation sources, comes with a shelf life. These problems at TVA are a specific instance of a more general circumstance: U.S. nuclear plants are largely all of the same vintage, meaning a nuclear cliff looms ahead for American utilities reliant on nuclear power.[165]

The purpose of this brief note on nuclear power is to provide a fuller view of TVA's economic and power generation circumstances and the

141. *Compare* DAVID HUME, A TREATISE OF HUMAN NATURE BEING AN ATTEMPT TO INTRODUCE THE EXPERIMENTAL METHOD OF REASONING INTO MORAL SUBJECTS 468–470, 474 (1896).

types of considerations that may be present in a fuller electric utility analysis. It also provides further context for the magnitude of the challenge of decarbonization for TVA. To wit, picking up the previous delimit of the Existing Set, recall that TVA can replace only approximately ten percent of its coal generation with natural gas and still meet the 80/2050 Goal. It then follows that none of its nuclear generation can be replaced by natural gas power even if the selected emissions performance objective were replaced by a looser measure. The nearly 4,914 MW of nameplate nuclear generation coming off license by 2036 would, instead, need to be secured from either relicensed/replacement nuclear generation, or a mixture of renewables and energy efficiency. These considerations would naturally impact a more detailed counting analysis.

IV.Conclusion

Marginal rate analysis is a powerful tool for seeking efficient outcomes from the incremental, continuous type of change that experience indicates is most common. Decarbonization is not a problem of continuity, however. The application of marginal rate analysis to decarbonization is therefore often misconstrued, described here in the discussion of the issues of Continuity and Abstraction Biases. Counting provides a useful corrective against problem misconstruction that proceeds from unsubstantiated assumptions of continuity.

Specific to decarbonization, a counting approach is offered as a useful augment to existing analytical approaches because it reduces the problem to its discrete causes, the technological inputs which result in greenhouse gas emissions. What matters in counting is the number of discrete technological substitutes necessary to reduce carbon dioxide emissions. This is a seemingly obvious observation obfuscated by a marginal focus on resultant continuous emissions and short run efficiency.

Counting carbon provides a different framework for understanding the problem of decarbonization—the correspondence between an Existing Set of technologies that must be replaced and a New Set of technologies that must be deployed. Even this simplified model of Equivalent Substitution Analysis (which holds promise for development) allows the observation that, at the set level, there is relatively more practical and theoretical potential for improvement in the technological artifacts that constitute the New Set, as contrasted with the Existing Set. Several consequences follow from this Improvement Gap.

One result is that substitutions of elements of the Existing Set for elements of the New Set can be expected to occur over time; thus, expressing a preference for decarbonization is simply articulating a temporal preference. Another outcome is that decarbonization is not precisely a problem of collective action. Rather, decarbonization is shown to be a problem that requires timely, targeted action from those with expressed normative preferences for reducing greenhouse gas emissions. The reason is that the process of adoption (the concept of "dispersion" in the technological change literature)is determinative in realizing the Improvement Gap. As a result, decarbonization actions can be made to have strategic effect even without broad social agreement, as the case study indicates.

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