THOMAS M. TURNBULL*

Redefining Efficiency: US Physicists and the 1970s Energy Crisis

ABSTRACT

Amid a war in Southeast Asia, fomenting campus radicalism, and a looming energy crisis, a number of physicists shifted from the big science endeavors of post-war physics toward a new and little science of energy efficiency. These moves were actively supported by the American Physical Society, which took various ongoing crises as an opportunity to create employment opportunities and harness enthusiasm for more socially engaged physics. The Society's 1974 Summer School on efficient energy use was illustrative. Participants came from universities, national laboratories, industry organizations, and utility companies. Together, they estimated efficiency savings believed achievable at certain points in the US energy system. The summer school attendees argued energy efficiency should be redefined according to the second law of thermodynamics rather than the first. This approach allowed energy-using appliances to be reconceived of as sources of energy *supply* as well as demand. Rigorous estimates of potential savings were made. However, to the ire of more radical physicists, the school placed the onus to conserve on the consumer, ignored industrial energy use, and had avoided drastic measures. In revisiting these events, their lead-up and afterlife, this paper historicizes a now-central tenet of energy policy.

KEY WORDS: American Physical Society, Energy History, Energy Conservation, Energy Crisis, Applied Science, Radical Science, Square Science

*Max Planck Institute for the History of Science, Berlin, tturnbull@mpiwg-berlin.mpg.de

The following abbreviations are used: AIP, American Institute of Physics Archive, College Park, Maryland; LBL, Lawrence Berkeley Laboratory Archives and Records Office, Berkeley; HSHS; *Historical Studies in the Natural Sciences*; HSPBS, *Historical Studies in the Physical and Biological Sciences*; HSPS, *Historical Studies in the Physical Sciences*.

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ENVIRONMENTALIST PHYSICS

In 1967, thirty-year-old historian of science Paul Forman argued quantum physics had reflected a wider rejection of strict principles of causation by certain intellectuals in Weimar Germany. He considered this an epiphenomenon of the uncertainties engendered by the country's defeat in the First World War. In making this claim, he leant on Oswald Spengler's *The Decline of the West* (1918), which described Occidental society's degradation and the effect of this on intellectual life.[1] Forman's thesis emerged from Thomas Kuhn's Berkeley-based research group Sources for History of Quantum Physics, a project that reconstructed the quantum revolution by interviewing and combing the papers of leading German physicists.[2] On this basis, Forman proposed an "environmentalist" method for historians of science, based on the idea that the environment shaped knowledge and the environment knowledge.[3] His method has since invited as much criticism as praise, but here this debate is side-stepped and his argument is taken more as an object of historiographic rather than historical interest, a reflection of late-1960s North America rather than 1920s Germany.[4]

We begin with Forman, an observer of the physics environment at the time, in order to situate the energy-saving turn in a specific context. Forman's environmentalism was not meant in the sense of environmental concern. In fact, as we will see, he was scathing about that movement. Instead, he meant a form of historicism that took the political and institutional contexts of knowledge formation seriously. The Weimar-era environment was marked by various crises, which Forman argued affected physics.[5] Focused on Alfred Landé's interwar work, Forman argued university crises, hostile publishers, and

1. Paul Forman, "The Environment and Practice of Atomic Physics in Weimar Germany" (PhD dissertation, University of California, Berkeley, 1967), 14, 56–57; "Weimar Culture, Causality, and Quantum Theory, 1918–1927: Adaptation by German Physicists and Mathematicians to a Hostile Intellectual Environment," *HSPS* 3 (1971): 1–115, on 30–37.

2. John Heilbron, "Quantum Historiography and the Archive for History of Quantum Physics," *History of Science* 7, no. 1 (1968): 90–111; Anke te Heesen, "Thomas S. Kuhn, Earwitness: Interviewing and the Making of a New History of Science," *Isis* 111, no. 1 (2020): 86–97, on 92–95.

3. Forman, "Environment" (n.1), iv.

4. Akin to David Cassidy, "Paul Forman and the Environment and Practice of Quantum History," in *Weimar Culture and Quantum Mechanics: Selected Papers by Paul Forman and Contemporary Perspectives on the Forman Thesis*, ed. Cathryn Carson, Alexei Kojevnikov, Helmuth Trischler, 263–76 (London: Imperial College Press, 2011); Jon Agar, *Science in the Twentieth Century and Beyond* (London: Polity, 2012), 118–41.

5. Agar, *Science* (n.5), 129.

economic inflation had forced Landé and others to "adapt the content of their science to the values of their intellectual environment." The late 1960s were similarly crisis-ridden. Economic and political crises were accompanied by more novel environmental and energy crises. As in Weimar Germany, Forman believed this changing environment had epistemological consequences. In a lengthy paper, he described how recent crises had created Weimar-like "resentment and antagonism toward the scientific enterprise," a reprised existentialism. Worse still, "concessions" were being "made to these same sentiments within the sciences themselves."[6]

Forman noted these concessions. They included physical chemist Franklin Long's advocacy for "interdisciplinary problem-oriented" research, and particle physicist Marvin Goldberger's call for universities to train environmentally concerned physicists—meant in the now-conventional sense.[7] In the *Physics Today* article Forman cited, Goldberger, Princeton's physics chair, described a 1969 meeting at Stanford in which an interdisciplinary team assessed a planned airport near Florida's Everglades National Park. Goldberger argued the "single most important technical contribution" had come from two young physicists, John Harte and Robert Socolow, who argued the airport would destroy West Florida's water supply. Goldberg suggested their testimonies had been critical to the plan's termination.[8] Forman, by contrast, took such events as signs of the "astonishing sincerity" with which physicists had conceded to "manifestly antiscientific sentiments."[9] He pejoratively termed their actions "neo-Spenglerian" in recognition of the cultural rather than scientific rationales.[10] In Forman's view, Weimar-era physicists had subverted conventional notions of causation to develop quantum physics, whereas the crises of his era had led only to a compromised environmentalist physics. Far from an "ecology' fad," as Forman dismissively termed such work, this paper argues

6. Forman, "Weimar" (n.1), 3–5.

7. Forman, "Weimar" (n.1), 5n4; among others, he cited Charles Long, "Interdisciplinary Problem-Oriented Research in the University," *Science* 171, no. 3975 (1971): 961; Marvin Goldberger, "How Physicists Can Contribute," *Physics Today* 23, no. 12 (1970) 26–30.

8. Goldberger, "How Physicists Can Contribute" (n.7), 26; on Stanford's approach to interdisciplinarity see Cyrus Mody, *The Squares: US Physical and Engineering Scientists in the Long 1970s* (Cambridge, MA: MIT Press, 2022), ch. 2.

9. Forman, "Weimar" (n.1), 5.

10. Forman described Spengler's "doctrinal touchstone" as the idea that science is "simply and solely an expression for the soul of that particular culture" rather than something universally true. Forman, "Environment" (n.1), 31, 57.

that growing interest in the problem of energy helped make environmentalist physics highly influential, shaping careers, institutions, and ideas.[11]

To understand this movement, we regroup a cast of North American physicists. Alvin Weinberg, Arthur Rosenfeld, and Robert Socolow represent a moderately radical faction, a type others have termed "squares" or "institutional agitators," who turned from or added to conventional physics to address energy profligacy and its consequences.[12] These physicists are contrasted with the more trenchantly radical David Jhirad, the more pragmatic radical Marc Ross, and the entrepreneurial activist Amory Lovins, who all wanted to save energy but thought this required deep social and political transformations. Together, this loose coalition exemplify a wider energy conservationist turn in physics. Moreover, this energy-saving movement can be seen as a subset of a wider-applied physics turn in the 1970s.

In his article Goldberger admitted the post-war "folklore" had been that "physicists can not only do anything" they "can do it better than anyone else," so it was no surprise that physicists had "became seriously involved with environmental problems."[13] For today's historians of science, the development of an environmentally concerned energy physics should also be unsurprising. Far from a generalizable anti-scientific era of the kind Forman decried, the 1970s are now recognized as a decade of remarkable productivity and eclecticism in science. Amid myriad crises, and as the conventions of Cold War funding loosened, people found alternative opportunities, careers, institutions, ideas, ways of being, and ways of doing physics.[14]

Though a lament, Forman's famous paper acknowledged this new pluralism. The concessions he identified, "ideological tendencies," encouraged environmentalist physicists to redefine energy efficiency. In doing so, as we will see, they helped shift the onus to conserve energy from energy producers to

11. Forman, "Weimar" (n.1), 40.

12. Squareness, as Mody argues, is a "relational category," Mody, *Squares* (n.8), 12; Deborah Poskanzer, "Art Rosenfield Interview AR deep bio," oral history interview, unknown date, shared with author on Jul 20, 2019, used with permission.

13. Goldberger, "How Physicists Can Contribute" (n.7), 26.

14. David Kaiser, *How the Hippies Saved Physics: Science, Counterculture, and the Quantum Revival* (New York: W.W. Norton, 2011); Matthew Wisnioski, *Engineers for Change: Competing Visions of Technology in 1960s America* (Cambridge, MA: MIT Press, 2012); Patrick McCray, *The Visioneers: How a Group of Elite Scientists Pursued Space Colonies, Nanotechnologies, and a Limitless Future* (Princeton, NJ: Princeton University Press, 2013); David Kaiser and W. Patrick McCray, eds., *Groovy Science: Knowledge, Innovation, and American Counterculture* (Chicago: University of Chicago Press, 2016); Mody, *Squares* (n.8).

consumers. The idea was that conservation could be achieved via more efficient appliances. To the dismay of true radicals, who sought deep structural changes, this meant corporations were entrusted to sell both the problem (energy) and perceived remedy (efficient appliances). In a sense, as historian Cyrus Mody argues of the era's move toward applied physics more generally, while such science was not doctrinally neoliberal, the federally led call for application encouraged a more market-orientated kind of science.[15]

NEW WINE

After the war, the US Atomic Energy Commission (AEC) repurposed Manhattan Project laboratories into regional nodes in a government-owned network of contractor-operated nuclear research centers.[16] Oak Ridge National Laboratory (ORNL) in Tennessee focused on isotope development.[17] Argonne and Brookhaven developed reactors and carried out commercial, non-classified research.[18] Those at Los Alamos remained largely dedicated to weapons research. From 1952, San Francisco's Livermore, competed with it. Lawrence Berkeley Laboratory (LBL), though a university lab, managed both and carried out AEC research. Between the war's end and the mid-1960s, the federal government spent eight billion dollars on these facilities.[19] Irrespective of this spending, nuclear power had stalled. By the late 1960s, the electrical utility industry that the AEC's research fed into was struggling to meet demand.[20]

Institutional reorganization is central to our story. In April 1973, the National Science Foundation (NSF) organized an "Energy R&D Task Force," headed by nuclear chemist Paul Donovan, which called for a wide-ranging approach to energy provision.[21] The 1974 "Energy Reorganization Act'

15. Mody, *Squares* (n.8), 38.

16. Peter Westwick, *The National Labs: Science in an American System, 1947–1974* (Cambridge MA: Harvard University Press, 2003), 10–14.

17. Robert Seidel "Accelerating Science: The Postwar Transformation of the Lawrence Radiation Laboratory," *HSNS* 13, no. 2 (1987): 375–400, on 377.

18. Hallam Stevens, "Fundamental Physics and Its Justifications, 1945–1993," *HSPBS* 34, no. 1 (2003): 151–97, on 157–58.

19. Westwick, *National* (n.17), 18; Robert W. Seidel, "A Home for Big Science: The Atomic Energy Commission's Laboratory System," *HSPBS* 16, no. 1 (1986): 135–75, on 137–39.

20. James Andover, "About That Power Crisis," *IEEE Spectrum* 10, no. 3 (1973): 72–73.

21. Jay Hammel, *Los Alamos Scientific Laboratory Energy-Related History, Research Managerial Reorganization Proposals and Actions Taken and Results, 1945–1979*, LA-13072-H (Los Alamos: Los Alamos Laboratory, 1997), 26.

dissolved the AEC.[22] National labs now served a Nuclear Regulatory Committee (NRC) and an Energy Research and Development Administration (ERDA), which three years later became the Department of Energy (DOE).[23] Historian Peter Westwick described this as federal government pouring "the old wine of the AEC into the new bottle of ERDA and the Department of Energy."[24] This underplays the new developments in energy supply that emerged. As Westwick himself showed, the AEC's widened remit led nuclear labs to study energy in general. As examples, Argonne sought to reduce sulfur emissions from coal combustion using a method derived from uranium hexafluoride production, a parabolic solar energy collector was fashioned from a radiation detection device, and Brookhaven explored lossless electrical "superconductivity."[25] Fuller histories of these alternative energy projects deserve to be told, but here our concern is these labs' work on *reducing* energy use.

APPLIED ENERGY

The national labs' turn to energy in general was partly shaped by straitened financial circumstances. The post-war period had been a bonanza for federally funded science. In 1953, the United States spent nearly fifty million dollars on *basic* physics, twenty times more than before the war.[26] Good times continued until 1969, when—as is well known—Senator Mike Mansfield pushed through a legislative amendment that prohibited the Department of Defense (DOD) from financing research that was not directly related to military objectives.[27] The amendment's boosters argued basic science funding was a dereliction of the government's fiduciary duty to taxpayers.[28]

22. Alice Buck, *A History of the Atomic Energy Commission,* DOE/ES-0003/1 (Washington, DC: Department of Energy, 1983), 6–7.

23. Leland Johnson and Daniel Schaffer, *Oak Ridge National Laboratory: First Fifty Years* (Memphis: University of Tennessee Press, 1994), 155.

24. Westwick, *National* (n.16), 270.

25. Westwick, *National* (n.16), 292–93.

26. Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States," *HSPS* 18, no. 1 (1987): 149–229, on 189–90.

27. Philip M. Boffey, "Mansfield Amendment Not Yet Dead," *Science* 170, no. 3958 (1970): 613.

28. Otto Larsen, *Milestones and Millstones: Social Science at the National Science Foundation* (New Brunswick, NJ: Transaction, 1992), 126.

Moreover, although Congress increased the NSF's budget for basic and applied science by eighty-five million dollars in 1969, and ten million in 1970, inflation dwarfed these outlays. In real terms, physics funding fell by a third between 1967 and 1976.[29] In this environment, there were reasons to re-evaluate the case for basic science.

Another aspect of the move to applied science was a "manpower" crisis.[30] As inflation deflated federal funding, the number of qualified physicists grew.[31] At the 1969 APS meeting, 1,300 applicants jostled for 234 jobs. By 1970 1,010 fought for just 63.[32] Looking for solutions, in 1972 the National Academy of Science (NAS), the Federal advisory organization, published *Physics in Perspective,* a thousand-page survey that set out alternative, socially relevant employment paths that avoided the narrow specialization of post-war years.[33] Just three years earlier, a similar NAS Committee had published *Physics: Survey and Outlook* in a period in which federal funding "justified extrapolation of the needs and objectives of the field on the basis of internal considerations."[34] Now, an applied, externally focused kind of physics was seen as one way to address unemployment in physics.

As the risk of energy shortages became clearer, *Physics in Perspective* suggested an energy crisis might prove an opportunity. As mentioned, in advance of the AEC's dissolution, Congress had revised the 1970 Atomic Energy Act. Section 31 paragraph 6 now gave the AEC a "general responsibility for research on energy" rather than research on nuclear power alone. Moreover, the report recommended Federal spending "reflect the seriousness of the energy problems of the United States and the world" and that the "research appropriations of this agency should be increased substantially."[35] Revised again in June 1971, it committed the AEC to the "preservation and enhancement of a viable environment by developing more efficient methods to meet the Nation's energy

29. David Kaiser, "When Fields Collide," *Scientific American* 296, no. 6 (2007): 62–69, on 67.

30. A term reflecting the underrepresentation of women physicists. D. Allan Bromley, "Physics in Perspective," *Physics Today* 25, no. 7 (1972): 23–35.

31. Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America*, 3 rd ed. (1971; Cambridge, MA: Harvard University Press, 1995), 412.

32. Kaiser, "Cold War Requisitions, Scientific Manpower, and the Production of American Physicists after World War II" *HSPBS* 33, no. 1 (2002): 131–59, on 151.

33. Dave Allan Bromley, *Physics in Perspective*, vol., 1, *Physics Survey Committee* (Washington, DC: National Academy of Sciences, 1972), 1–109.

34. Bromley, *Physics in Perspective* (n.33), 23–24.

35. Bromley, *Physics in Perspective* (n.33), 17.

needs."[36] Alongside amendments, in 1969, the NSF also changed tack, allocating funds to *applied* as well as basic science.[37]

Historian David Kaiser has demonstrated how, in straitened times, "other modes of being a physicist crept back in."[38] His example was Berkeley's *Fundamental Fysiks* group, who turned to esoteric topics like Bell's theorem and parapsychology. Others sought relevance and commercialization: Cyrus Mody documented how industrial physicist Philip Wyatt repurposed an inverse-scattering particle characterizer to monitor pollution;[39] and how inventor of the integrated-circuit Jack Kilby tried to commercialize a domestic solar energy.[40] Speculatively, and with an eye on book sales, physicist Gerald K. O'Neill promoted the idea of solar-energy-harvesting satellites, as Patrick McCray recounts.[41] Myself and Mody have described how budget-stricken NASA scientists repurposed satellite-borne photovoltaics to collect solar power on Earth.[42] One aim is to show, rather than these other ways of being a physicist creeping in, the physics establishment actively promoted energy demand as an opportune problem for a discipline otherwise experiencing "deteriorating support."[43]

A CONSERVATIVE ENVIRONMENT

At the 1968 Democratic Party Convention, Berkeley physicist Charles Schwartz led a coalition that called on the AAAS to denounce the violent suppression of anti-war protesters. Incensed by their refusal, at the 1969 APS meeting, Schwartz and Herb Fox, a fellow anti-war activist, announced the

36. Westwick, *National* (n.16), 291; Johnson and Schaffer, *Oak Ridge* (n.23), 155.

37. Thomas Turnbull and Cyrus Mody, "Turn and Turn Again: How Big Science Both Helped and Hindered Alternative Energy in the 1970s," in *Big Science in the 21st Century: Economic and Societal Impacts*, ed. Pangiotis Charitos, Theodore Arabatzis, Harry Cliff, Günther Dissertori, Juliette Forneris, and Jason Li-Ying (Bristol: IOP Publishing, 2023): 31-1–31-21; Johnson and Schaffer, *Oak Ridge* (n.23), 150–51.

38. Kaiser, *Hippies* (n.14), 20–21.

39. Mody, *Squares* (n.8), 58–59.

40. Mody, *Squares* (n.8), 180–85.

41. McCray, *Visioneers* (n.15), 70–71.

42. Turnbull and Mody, "Turn," (n.37).

43. Joseph Martin, *Solid State Insurrection: How the Science of Substance Made American Physics Matter* (Pittsburgh: University of Pittsburgh Press, 2018); On "deteriorating support" Bromley, *Physics in Perspective* (n.33), 501; Even the American Vacuum Society turned toward solar power, Mody, *Squares* (n.8), 43.

formation of Scientists and Engineers for Political Action (SESPA), which they presented as a radical counterweight to the science establishment.[44] Physicists Martin Perl, Michael Goldhaber, and Marc Ross co-signed SESPA's founding declaration.[45] Ross, a high-energy physicist from the University of Michigan, was considered a "kind of passive" signatory and co-author by Schwartz, though he later became an active radical.[46] Raised in Baltimore by Ukrainian-Belgian parents, Ross studied physics at Chicago, and took classes with Edward Teller. He completed a PhD at Wisconsin and briefly worked at Brookhaven and Argonne.[47] In the 1970s, various looming crises encouraged him to teach a "Societal and Environmental Physics" course focused on the problems of pollution and arms control.[48] He later specialized in automotive engine efficiency, for which he was awarded the Szilard Prize.[49] This trajectory, from APS antagonist to prize winner, indicates how energy-saving physics moved from a challenge to mainstream physics to something rewarded by it.

When Ross was still considered a radical, at the 1970 AAAS meeting, SESPA condemned the organization's president and AEC director Glenn Seaborg for supporting "science against the people."[50] SESPA's antics there are well known: Teller, "father" of the H-bomb, was mockingly given a Dr. Strangelove award; Jane Swanson, wife of biologist Garett Hardin, stabbed a protestor with a hatpin;[51] Kuhn's historians attended, though Forman was unwell.[52] Less well remembered is SESPA's accusation that Seaborg had made scientists corporate shills. As Seaborg ducked out, he was condemned over a megaphone

44. Kelly Moore, *Disrupting Science: Social Movements, American Scientists, and the Politics of the Military, 1945–1975* (Princeton, NJ: Princeton University Press, 2013), 146; Mody, *Squares* (n.8), 1–2.

45. SESPA, "Scientists Dedicated to Vigorous Social and Political Action," self-published, 1969. http://science-for-the-people.org/wp-content/uploads/2014/02/SftP-SESPA_founding-document-3.pdf

46. Patrick Catt, AIP Interview with Charlie Schwartz, Jul 19, 1995. www.aip.org/history-programs/niels-bohr-library/oral-histories/5913

47. Jens Zorn, Overview of 2007 Interview of Marc Ross. https://lsa.umich.edu/content/dam/rc-assets/rc-documents/Ross%202007%20Interview%20by%20JCZ%20version%20of%2027%20Nov%202017%20(2).pdf

48. John Fowler, "The Environmental Theme in Physics Education," *Annual Meeting of the Association of Physics Teachers*, Jan 31, 1972, 1–15, on 13.

49. Katherine Clay, Gordon Kane, Brandon Orr, Rob Socolow, and Robert H Williams, "Obituary: Marc Hansen Ross," *Physics Today* (online) Aug 16, 2018, https://pubs.aip.org/physicstoday/online/5506/Marc-Hansen-Ross.

50. Moore, *Disrupting* (n.44), 167.

51. Kevles, *Physicists* (n.31), 403; Moore, *Disrupting* (n.44), 166–67.

52. Cassidy, "Paul Forman" (n.4), 268.

for helping uphold "world hegemony for the profit-making, people-exploiting American empire."[53]

If SESPA held that science was detrimentally commercialized, fiscal conservatives like Mansfield thought its commercial benefits were overstated.[54] Amid stagflation, Nixon's government began to promote a market-orientated *applied* science.[55] Curiously, both a radical left and emergent "New Right" were engaged in criticizing state-funded science.[56] Another constituency, exemplified by Kilby, was pragmatic. Kirby wanted to commercially fabricate 250-micron-sized silicon balls for generating solar power. In seeking private funding, he and other entrepreneurial scientists were motivated by personal gain rather than beliefs.[57] Amid these re-evaluations of science's economic role, other physicists turned to energy saving. Some considered this radical, while others found it disappointingly conformist.

CONSERVATION PRINCIPLES

It is worth emphasizing the status of conservation principles in high-energy physics (HEP). Accelerators used electricity to accelerate particles at high velocities in a vacuum, which were then fired into obstacles and disintegrated into subatomic matter.[58] More powerful accelerations at higher currents revealed ever-greater detail about particles and their energy. As accelerators grew, HEP became the archetypal "big science," particularly in terms of cost.[59] Understandably, as more energy revealed more details about subatomic matter, efficiency became a concern. By the 1980s, Fermilab's Tevatron had a superconducting second ring, nicknamed the "energy saver," which halved the

53. The Boston Travellers, "Chicago '70 AAAS Actions: Review and Critique," *Science for the People* 3, no. 1 (1971): 8–11; SESPA, "Indictment of Glenn T. Seaborg," *Science for the People* 3, no. 1 (1971): 12.

54. Kevles, *Physicists* (n.31), 410–14.

55. Bethany Moreton, "Make Payroll, Not War," in *Rightward Bound: Making America Conservative in the 1970s*, ed. Bruce J. Schulman and Julian E. Zelizer, 52–70 (Harvard University Press, 2008), 63–64.

56. Walter McDougall, "The Cold War Excursion of Science," *Diplomatic History* 24, no. 1 (2000): 117–127, on 124.

57. Mody, *Squares* (n.8) 192.

58. David Cassidy, *A Short History of Physics in the American Century* (Cambridge, MA: Harvard University Press, 2011), 53–56.

59. Peter Westwick, "High-Energy Physics," in *The Oxford Companion to the History of Modern Science* ed. John Heilbron, 364–66 (Oxford: Oxford University Press, 2003).

demand of its trillion-electron volt accelerator.[60] Such practical efforts no doubt fed into the science of saving energy.

Conservation principles were critical to particle physics.[61] In bubble-chamber analysis, a stream of particles was directed at a pressurized tank of liquid hydrogen, simple nuclei held just below boiling point. The path of charged particles through this liquid left a trail of bubbles indicative of momentum, energy, mass, and rate of decay. Mechanized cameras harvested huge numbers of trail images.[62] Labor-saving means of image analysis were sought.[63] Luis Alvarez's Berkeley lab famously developed the "Frankenstein," a device named after engineer Jack Frank, which drove a cursor along a trail image, logging coordinates.[64] In an article outlining their method, Alvarez's group described how, in classifying particles, they took "advantage of the fact that nature conserves many quantities (in addition to energy and momentum) and shows various symmetries (such as between left and right)."[65] Such regularities in mass, angular momentum, charge, and energy remain constant and affirm known physical laws.[66] So beyond practical economization, conservation was a benchmark against which particle "events" could be measured and classified.[67]

Alvarez's team were early adopters of computers. Having worked with the Manhattan Project's MANIAC 1 computer, Alvarez recognized the role computers could play in particle physics. In 1956, he hired Frank Solmitz to write code that analyzed Frankenstein-derived data. Another student of Fermi's, Rosenfeld, was hired to work on code to improve heat-track analysis. In 1968, Alvarez received a Nobel Prize for developing the hydrogen bubble chamber and discovering numerous particles, but also in recognition of his

60. Lilian Hoddeson, "The First Large-Scale Application of Superconductivity: The Fermilab Energy Doubler, 1972–1983," *HSPS* 18, no. 1 (1987): 25–54, on 26.

61. Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics* (Chicago: University of Chicago Press, 1985), 50.

62. Peter Galison, "Bubble Chambers and the Experimental Workplace," in *Observation, Experiment, and Hypothesis in Modern Physical Science*, ed. Peter Achinstein and Owen Hannaway, 309–73 (Cambridge MA: MIT Press, 1985), 340–41.

63. Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: Chicago University Press, 1997), 315.

64. Robert Seidel, "From Mars to Minerva: The Origins of Scientific Computing in the AEC Labs," *Physics Today* 49, no. 10 (1996): 33–39, on 36–37.

65. Geoffrey Chew, Murray Gellman, and Arthur Rosenfeld, "Strongly Interacting Particles," *Scientific American* 210, no. 2 (1964): 74–93, on 80.

66. John Daintith ed., *Dictionary of Physics* (Oxford: Oxford University Press, 2000), 74–75.

67. Stevens, "Fundamental" (n.18), 180.

group's creation of a computer-aided system for studying energetic events.[68] While claiming neither exclusivity nor definitiveness, it will become clear that particle physicists' concern with economization, conservation laws, and computer programming all fed into the physics of saving energy.

NUCLEAR FALLOUT

Alvarez's lab attracted controversy. In 1972, Berkeley's SESPA branch revealed Alvarez was part of the JASONs, an elite cadre of physicists who presented the Pentagon with high-tech ways to fight the Vietnam War.[69] For the Bay Area SESPA members, the lab's relations to the nuclear industry also invited criticism. A 1976 pamphlet lead-authored by Berkeley physicist Martin Brown pointed out that the wider University of California received hundreds of millions of dollars of research funding from the nuclear industry, via the AEC, and that some professors had ties to both.[70] More generally, Brown and coauthors argued that utility companies, not energy consumers, were demanding new nuclear plants. Companies like General Electric (GE) issued forecasts warning electricity demand would increase by 7.5 percent per year, as if this was independent from their own actions.[71] Given the time needed to build a plant, such forecasts were in fact performative, encouraging investors and regulators that construction was necessary.[72] GE had promoted profligacy with the slogan "Live Better Electrically" in advertisements starring then-actor Ronald Reagan.[73] SESPA described these ads as part of a wider strategy whereby utilities "pushed one appliance after another into the home and urged industry to use more electricity by offering lower rates to big users."[74]

68. Robert Seidel, "From Factory to Farm: Dissemination of Computing in High-Energy Physics," *HSNS* 38, no. 4 (2008): 479–507.

69. Berkeley SESPA, *Science Against the People* (Berkeley, 1972), 24.

70. Martin Brown, Pamela FitzGerald, Merry Goodenough, David Hollenbach, Jeff Pector, Charles Schwartz, and Joel Swartz, "Nuclear Power: Who Needs It?," *Science for the People* 8, no. 3 (1976): 4–12, on 11.

71. See Martin Brown ed., *The Social Responsibility of the Scientist* (London: Macmillan, 1971).

72. Thomas Turnbull, "California's Quandary: Saving Energy at the RAND Corporation," *Environmental History* 28, no. 4 (2023): 738–65.

73. Tim Raphael, "The Body Electric: GE, TV and the Reagan Brand," *The Drama Review* 53, no. 2 (2009): 113–38.

74. Brown et al., "Nuclear" (n.70), 5.

This profit-making apparatus was not only approved but also heavily subsidized by government. Alongside research, uranium exploration, energy-intensive enrichment, transport, and waste storage enjoyed considerable state support. As such, for SESPA, the AEC and its supporting labs acted "to protect the special interests of big business and the military"—a lucrative arrangement with a fissionable by-product. State was tied to industry. The Atomic Industrial Forum (AIF), a longstanding lobby group linked to the AEC, represented utility and oil companies with a stake in nuclear power. Thanks to oil price–driven "diversification," the seven major oil companies owned 30 percent of US coal and between 50 to 80 percent of US uranium reserves. Interlocking directorships were also common, evidence of an "atomic-industrial complex," with the AIF acting as "propaganda arm of a vast energy monopoly."[75]

Even among squares, enthusiasm for nuclear power was waning. Enrollment in nuclear engineering courses peaked in 1975, falling 25 percent by the decade's end.[76] In part, this was because the technology's risks had become widely publicized. Utility companies had been reluctant to invest in nuclear power without Federal indemnity. This had created one of the subsidies radicals later condemned. The Price-Anderson Act, passed in 1957, meant government would pay out in the event of a disaster. The case rested on an AEC study that predicted an accident would be so catastrophic that no private insurers could shoulder the risk. Brookhaven's "WASH-740" report claimed reactor failure would result in thousands of deaths and billions in property loss. A 1965 update raised this to 45,000 fatalities and $17 billion in damages. The AEC concealed this, but the figures were leaked a year later, startling investors. In 1966, utility companies had pledged to develop thirty-one nuclear power plants, but by 1972 only ten were built.[77] That year, research into "emergency core cooling systems" generated so much paperwork, dissent, intimidation, and criticism within the AEC that legislators decided to fold the organization, creating ERDA and the NRC.[78] The nuclear industry and its underlying research labs were already faltering as SESPA critics weighed in.

75. Brown et al., "Nuclear" (n.70), 8.

76. Don Johnson, *Nuclear Engineering Enrollments & Degrees Survey Data 50-Year Trend Assessment*, 1966–2015 (2017). https://orise.orau.gov/stem/reports/ne-assessment-2017.pdf

77. James Golden, "APS Considers Plan for Energy Study," *Physics Today* 26, no. 11 (1973): 69–70.

78. Thomas Wellock, "Engineering Uncertainty and Bureaucratic Crisis at the AEC, 1964–1973," *Technology and Culture* 53, no. 4 (2012), 846.

If SESPA sought to transform science, Washington, DC–born Lovins left it for entrepreneurial activism. Lovins studied physics at Harvard and moved on to a fellowship at Oxford in 1968. On holiday he took photos in Snowdonia, Wales, to raise awareness of Rio Tinto's intention to mine zinc in this national park.[79] He sent these to fellow climber David Brower by way of appeal. Brower formerly directed the nature conservationist Californian Sierra Club. Finding the Club too moderate, he left to set up the more radical Friends of the Earth (FOE) in 1969. Brower suggested Lovins leave academia and join FOE's London office.[80] Lovins turned his nuclear expertise on its head, publicizing on its risks and critiquing reactor designs in detail. He argued nuclear power was technically flawed, environmentally damaging, and easily weaponized.[81] Lovins demonstrated an alternative path for physicists: professional activism.

AN ECOLOGICAL PRIESTHOOD

If nuclear power and nuclear weapons were as inextricably linked as Lovins claimed, what were the martial implications of using less energy? To consider this, we turn to Oak Ridge Tennessee. In the 1930s, a federal works program had harnessed the Tennessee River to generate low-cost electricity. The river powered the production of aluminum, ammunition, and fissionable isotopes for the Manhattan Project. This facility, known as "X-10," was renamed ORNL in 1943.[82] Following the 1954 Nuclear Power Act, ORNL studied commercial nuclear reactors, soon backed by government indemnity.[83] Researchers also studied material physics, neutron irradiation, and even nuclear-powered flight. But as nuclear power provision stalled, energy saving also became a concern.[84] In recounting this turn, we will see how, in

79. Meredith Veldman, *Fantasy, the Bomb, and the Greening of Britain: Romantic Protest, 1945–1980* (Cambridge: Cambridge University Press, 1994), 223; Amory Lovins and David Brower, *Eyri, the Mountains of Longing* (London: Friends of the Earth, 1971).

80. Editors, "The Plowboy Interview with Amory Lovins," *Mother Earth News*, Nov–Dec., 1977; Jennifer Thomson, "Surviving the 1970s: The Case of Friends of the Earth," *Environmental History* 22, no. 2 (2017): 235–56.

81. Amory Lovins, *World Energy Strategies: Facts, Issues, and Options* (London: FOE, 1975), 108–10.

82. Johnson and Schaffer, *Oak Ridge* (n.23), 16; Thomas Hughes, "Tennessee Valley and Manhattan Engineering District," in *American Genesis: A Century of Innovation and Technological Enthusiasm 1870–1970* (Harmondsworth, Penguin): 353–442, on 379.

83. Robert Seidel, "Home for Big Science" (n.19), 157.

84. Johnson and Schaffer, *Oak Ridge* (n.23), 59.

a conservation-minded era, ORNL's military obligations mutated rather than disappeared.

The oldest of our main protagonists, Weinberg, studied biophysics at Chicago in the 1930s.[85] His mentor Eugene Wigner, with whom he worked on the wartime X-10 graphite reactor, encouraged him to apply for the ORNL research directorship, a position from which, by 1955, he rose to direct the entire lab.[86] Weinberg's acumen and ability to coin buzzwords, such as "big science" and "technological fix," both characterized and drove research agendas.[87] Alongside his enthusiasm for nuclear power and deterrents, his fixes tended to be energy-centric. At one point he argued that the 1965 Watts riots, conventionally understood as an outcome of decades of Los Angeles's racist policing, could have been avoided if residents had air conditioning. During that summer's heatwave, would-be-rioters, he argued, would have remained home in front of their televisions, placated by artificially cooled air.[88]

Weinberg believed science funding should be allocated to disciplines according to the degree to they contributed to neighboring disciplines. HEP rated poorly in this regard, while nuclear physics had "vast ramifications for neighboring fields."[89] Studies on irradiation and fallout had unexpectedly meant the AEC was the predominant funder of ecological research in the United States, and ORNL its most successful recipient.[90] Centipede specialist Stanley Auerbach was the lab's first ecologist, hired in 1954. Six years later, twenty-two ecologists worked at ORNL's Radiation Ecology lab. Fallout ecology waned following the 1963 partial ban on atmospheric bomb tests, leading ORNL to form a more general Environmental Sciences Division.[91] Ecology continued to evolve alongside nuclear physics, occasionally even impinging upon it: ORNL ecology backed up the "Calvert Cliffs" ruling, which required the federal government to demand stringent impact assessments for proposed

85. Martin, *Solid State* (n.43), 137.

86. Sean F. Johnston, "Alvin Weinberg and the Promotion of the Technological Fix," *Technology and Culture* 59, no. 3 (2018): 620–51.

87. Johnston, "Alvin" (n.86), 620.

88. Johnston, "Alvin" (n.86), 629–30.

89. Alvin Weinberg, "Criteria for Scientific Choice," *Minerva* 1, no. 2 (1963): 159–71, on 169.

90. Sharon E. Kingsland, *The Evolution of American Ecology, 1890–2000* (Baltimore: Johns Hopkins University, 2005), 180.

91. Stephen Bocking, "Ecosystems, Ecologists, and the Atom: Environmental Research at Oak Ridge National Laboratory," *Journal of the History of Biology* 28, no. 1 (1995): 1–47.

power plants.[92] In a speech, Weinberg astutely observed that "ecologists have displaced the physicists and the economists as high priests in this new era of environmental concern."[93]

ORNL's environmentalism was in step with public concerns. In April 1970, millions of North Americans celebrated the first "Earth Day," holding environmentally concerned teach-ins and protests.[94] Auerbach and other staff participated in Tennessee's events.[95] However, the lab's environmentalist credentials were questionable. Most staff still worked on nuclear technologies. ORNL had recently received permission to store "high-level" radioactive waste in a Kansan salt mine, and to develop a "super-duper" radioisotope cooker.[96] Such contradictions arose from Weinberg's apparent belief that environmental research should bolster nuclear research in lean times: ORNL was in fact the first successful applicant to the NSF's Nixon-era Interdisciplinary Research Relevant to Problems of Society (IRRPOS) program, gaining funding to study "The Environment and Technological Assessment"; success continued under the Research Applied to National Needs (RANN) program.[97] As ORNL's canteens were replaced by vending machines, Weinberg affirmed his lab's commitment to "an interdisciplinary attack on problems of the environment."[98]

MARTIAL CONSERVATION

ORNL's partial environmentalism did not mean the institution had rescinded on its martial obligations. In 1971, Nixon appointed former RAND Corporation analyst James Schlesinger as AEC chair. As noted, the AEC had received Congressional approval to investigate non-nuclear sources of energy, a move

92. Barry Nichols, "ORNL and the Calvert Cliffs Decision," *ORNL Review* 5, no. 4 (1972): 20–24.

93. Alvin Weinberg, "State of the Laboratory, 1969," *ORNL Review* 3 no. 3 (1970): 1–14.

94. Adam Rome, *The Genius of Earth Day: How a 1970 Teach-in Unexpectedly Made the First Green Generation* (New York: Farrar, Straus and Giroux), x–xi.

95. "Earth Day 1970," *ORNL Review* 25, nos. 3–4 (1992): 149.

96. Johnson and Schaffer, *Oak Ridge* (n.23), 131, 143; Samuel Walker, "An 'Atomic Garbage Dump; for Kansas: The Controversy over the Lyons Radioactive Waste Repository, 1970–1972," *Kansas History* 29, no. 4(2006–7): 266–85.

97. Turnbull and Mody (n.37); Alvin Weinberg, "From Technological Fixer to Think-Tanker," *Annual Review of Energy and the Environment* 19, no. 1 (1994): 15–36, on 25.

98. Alvin Weinberg, "State of the Laboratory—1970," *ORNL Review* 4, no. 2 (1971): 10; Leland and Schaffer, *Oak Ridge* (n.23), 152.

partly provoked by concerns about energy security. An Organization of Petroleum Exporting Countries (OPEC), formed in 1960 by Venezuela, Iran, Iraq, and other nations, had become increasingly assertive in seeking better renumeration for their oil: a significant part of the "foreign" supply upon which the United States depended.[99] Schlesinger imported RAND's supposedly post-ideological systems analytical approach."[100] Notably, RAND had begun studying energy conservation.[101] As AEC chair, Schlesinger proposed the "energy dilemma" be addressed in a similarly technocratic manner.[102]

US petroleum production peaked in 1971, the year the Soviet Union became the world's leading oil producer and OPEC sharpened its anticolonial position at a meeting in Tehran.[103] Though a period of détente, energy supply had become a security concern. In a 1972 speech to New York businesspeople, Schlesinger argued environmentalists had been right to challenge the "presupposition that irrespective of policy objectives and constraints, demand for energy grows."[104] He went on: "If we describe the increasing dependence on foreign fuels as a threat to the national security, to the balance of payments, or the steadfastness of foreign policy, then we would seem obliged to consider measures more drastic for conserving on energy use." So, he behooved his audience to "do somewhat better than automobiles that move at 10-miles to the gallon and badly insulated buildings."[105] As OPEC threatened an embargo, the AEC chair banged the drum for conservation as a means of national defense.[106]

Reading the runes, Weinberg insisted Schlesinger's "intelligent statement" be reprinted in ORNL's *1972 Annual Review.*[107] There, the

99. Nineteen percent of US oil consumption came from other countries. Giuliano Garavini, *The Rise and Fall of OPEC in the Twentieth Century* (Oxford: Oxford University Press, 2019), 190.

100. James Schlesinger, "Systems Analysis and the Political Process," P-3464 (Santa Monica, CA: RAND Corporation, 1968): 1–31.

101. Turnbull, "California's Quandary" (n.72).

102. James Cochrane, "Carter Energy Policy and the Ninety-Fifth Congress," in *Energy Policy in Perspective: Today's Problems, Yesterday's Solutions*, ed. Craufurd Goodwin, 547–600 (Brookings, Washington, DC, 1981), 553–54.

103. David Painter, "Oil and Geopolitics: The Oil Crises of the 1970s and the Cold War," *Historical Social Research* 39, no. 4 (2014): 186–208, on 204; Garavini, *Rise* (n.99), 198.

104. James Schlesinger, "The Energy Dilemma," reprinted in *ORNL Review* 5, no. 4 (1972): 8–15.

105. Schlesinger, "Energy Dilemma" (n.104), 13.

106. Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, and Power* (New York: Simon & Schuster, 1991), 661–62.

107. Schlesinger, "Energy Dilemma" (n.104), 9.

recycled talk implored ORNL physicists to develop strategic conservation measures.[108] Under the AEC's widened remit, Weinberg had already established a Conservation and Renewable Energy Program.[109] Projects on waste heat use, improved turbines, coal gasification, batteries, solar power, synthetic fuels, and home insulation followed.[110] The program's aim was to formulate new ways to supplement national energy use, or to find means for its reduction. A subgroup led by David Rose, a pro-nuclear environmentalist, and environmentalist-mechanical engineer Eric Hirst, measured efficiency increases in specific devices and scaled these up to estimate potential national savings.[111]

These lab-derived estimates were somewhat crudely extrapolated. For example, in 1971, Weinberg lauded ORNL physicist John Moyers for showing how a 20 percent increase in the efficiency of home insulation resulted in a 20 percent reduction in energy use.[112] This largely ignored the indeterminacies of economic behavior.[113] Moyers used a FORTRAN model to present energy demand as an almost mechanical outcome of changes to parameters such as wall thickness or roofing material.[114] The idea was that modeled efficiencies could be achieved in the built environment, particularly in standardized homes.[115] Such promising abstractions attracted the interest of Federal government. The head of ORNL's environment program, John Gibbons, was seconded to Nixon's hastily formed Office of Energy Conservation in early 1973.[116] As OPEC declared its embargo in October, energy efficiency became as much part of national security concerns as environmental or energy policy.[117]

108. Yergin, *The Prize* (n.106), 662.

109. Johnson and Schaffer, *Oak Ridge* (n.23), 172.

110. Allen L. Hammond, "Conservation of Energy: The Potential for More Efficient Use," *Science* 178, no. 4065 (1972): 1079–81; Johnson and Schaffer, *Oak Ridge* (n.23), 150.

111. Johnson and Schaffer, *Oak Ridge* (n.23), 150, 161; Carolyn Krause, "Household Energy Use: From Consumption to Conservation," *ORNL Review* 10, no. 4 (1977): 11–18, on 15.

112. Alvin Weinberg, "State of the Laboratory: 1972," *ORNL Review* 6, no. 1 (1973): 4.

113. John Moyers, *The Value of Thermal Insulation in Residential Construction*, ORNL-NSF-EP-9, 93–100 (Oak Ridge, TN: Oak Ridge National Laboratory, 1971): 23.

114. Moyers, *The Value of Thermal Insulation* (n.113), 97.

115. Johnson and Schaffer, *Oak Ridge* (n.23), 162–63.

116. Rosina Bierbaum and Neal Lane, "John Howard Gibbons," *Physics Today* 68, no. 12 (2015), 69–70.

117. Peter Auer, "Energy Self-Sufficiency," *Annual Review of Energy* 1 (1976): 685–713.

FERTILE SOIL

Universities were also conscripted in the fight to save energy. The University of California's LBL became a kind of national laboratory in 1971. There, Berkeley's most visually prominent accelerator, its cyclotron, sited above campus and overlooking San Francisco Bay, reminded students and faculty of the Faustian pact the university had made with US nuclear power.[118] The university still managed nuclear weapons research at Livermore and Los Alamos, to the ire of local radicals.[119] SESPA condemned the University of California's "uniquely close collaborations with the AEC," as not only did it receive as much 300 million dollars annually from the agency in the 1970s, Seaborg, former AEC director and alleged corporate shill, had been LBL's associate director and the university's chancellor. LBL carried out research for the AEC and assisted Brookhaven in its work, so it was little wonder it was seen as enmeshed in the atomic industrial-complex.[120] As the decade unfolded, the lab's researchers began studying energy saving, despite the very idea undermining the case for new nuclear plants.

The following section traces the career of Rosenfeld, a scientist who's evolving convictions would re-orientate not only his own work but ultimately the entire lab. Born in Birmingham, Alabama, to a father who was an expert in sugarcane, Rosenfeld spent part of his childhood in Cairo. He later studied industrial physics at Virginia Polytechnic, taught naval recruits to use radar, and studied physics at Chicago.[121] In 1954, he received a doctorate as the last student of Enrico Fermi, the famed Italian wartime nuclear physicist.[122] On Fermi's recommendation, Rosenfeld became an assistant professor at LBL in 1956.[123] Among physicists, he is perhaps best known for founding the Particle Data Group repository. To others, he is known for his subsidiary career. Diversifying his interests and grant-writing skills, he became a leading advocate

118. William J. Rorabaugh, *Berkeley at War: The 1960s* (Oxford: Oxford University Press, 1989): 168–69; Westwick, *National* (n.16), 28.

119. US Nuclear Weapons Conversion Project, "The University of California Operation of the Lawrence Livermore and Los Alamos Scientific Laboratories," in *Science and Liberation*, ed. Arditti, Rita, Pat Brennan, Steve Cavrak, 93–112 (Boston: South End Press, 1980).

120. SESPA, *Nuclear Power: A Science for the People Pamphlet* (Berkeley, 1976), 11; Seidel, "Accelerating" (n.17) 387; Seidel, "Home for Big Science" (n.19), 144.

121. Poskanzer, oral history interview (n.12).

122. Emilio Segré, *Enrico Fermi, Physicist* (Chicago: University of Chicago Press, 1970), 169.

123. Arthur Rosenfeld, "The Art of Energy Efficiency: Protecting the Environment with Better Technology," *Annual Review of Energy and the Environment* 24 (1999): 33–82.

for energy efficiency, later resulting in senior advisory roles at both the California Energy Commission (CEC) and the DOE.[124]

Rosenfeld was long politically engaged. He had joined Chicago's Federation of Atomic Scientists in the 1950s, a group of Manhattan Project veterans and younger scientists who sought to "control the atom" their discipline had unleashed.[125] Following a series of AEC announcements at the time that downplayed the genetic implications of radiation exposure, he and Sydney Warshaw placed Geiger counters on the roof of Chicago's Institute for Nuclear Studies to measure trace radiation from bomb tests in distant Nevada.[126] Each Thursday, they telephoned the *Chicago Tribune* to give a readout of detected exposure. Rosenfeld believed these disclosures encouraged the AEC to report more objectively on nuclear health risks.[127]

His rebellious approach took root in fertile soil. Berkeley's legacy of radicalism stretched back to before the war. This accelerated when dissident German émigrés arrived in the Bay Area. Sociologist Leo Löwenthal popularized the Frankfurt School's work on campus.[128] Beyond the humanists, in the 1970s, the aforementioned Schwartz and his SESPA comrades convened lunchtime meetings to read Ghandi and discuss the moral implications of science, much to the chagrin of LBL director Edwin McMillan, who sought Schwartz's dismissal. A 1971 issue of SESPA's journal, *Science for the People*, discussed Schwartz's case, noting Rosenfeld was "firmly committed to the cause"; even Alvarez, a "somewhat conservative member of the establishment" (a JASON no less) had offered "occasional support."[129] It was not enough. Schwartz was fired for "flagrant and repeated defiance of authority."[130] Nonetheless, the controversy revealed LBL's radical sympathies, which fed into the lab's conservation work.

124. Ashok Gadgil, David Goldstein, and Jonathan Koomey, "Arthur Hinton Rosenfeld," *Physics Today* 70, no. 9 (2017): 73.

125. David Kaiser and Benjamin Wilson, "American Scientists as Public Citizens: 70 Years of the *Bulletin of the Atomic Scientists*," *Bulletin of Atomic Scientists* 71, no. 1 (2015): 13–25.

126. Arthur Rosenfeld, E. J. Story, and S. D. Warshaw, "Fall-Out: Some Measurements and Damage Estimates," *Bulletin of the Atomic Scientists* 11, no. 6 (1955): 213–16.

127. Poskanzer, oral history interview (n.12).

128. Rorabaugh, *Berkeley* (n.118), 10–14.

129. SESPA, "Report from Berkeley SESPA," *Science for the People* 3, no. 2 (1971): 2; Mody, *Squares* (n.8), 5.

130. Finn Aaserud, Oral History interview with Charles Leon Schwartz, May 15, 1987, AIP, Niels Bohr Library Archives.

TURN OFF, TUNE IN, BUT DON'T DROP OUT

Rosenfeld never joined SESPA, but the 1973 oil embargo somewhat radicalized him. He recalled queuing for gasoline after work in November that year, during which he calculated the lab would consume one hundred gallons of fuel over the weekend despite the building remaining largely empty.[131] Rosenfeld returned to the office to turn lights off. He discovered switches concealed behind filing cabinets, posters, bookcases. Given what he had witnessed elsewhere, these signs of indifferent profligacy were illogical: when visiting the European Centre for Nuclear Research (CERN) to attend Alvarez's Nobel ceremony, he had noticed no real difference between his and Swiss people's quality of life, despite their using half the electricity of average North Americans.[132] Rosenfeld remembered this gas-station epiphany as the moment he realized "per-capita energy use could be reduced without deprivation."[133]

Rosenfeld's conservationist turn was timely. As budget's were squeezed, fundamental physics was still done at this and most national labs, but diversification became necessary. LBL's new director, Andy Sessler, assumed the role in late 1973. He established an Energy and Environment Division.[134] Beyond Berkeley, Rosenfeld's move also reflected wider disciplinary concerns. Since 1971, the APS had established a new division, the Forum on Physics and Society, which sought the "advancement and diffusion of knowledge regarding the interrelation of physics, physicists, and society."[135] The Forum was intended as a moderate counterweight to SESPA.[136] It addressed subjects,

131. Peter Galison, "FORTRAN and Human Nature," in *Image and Logic* (n.63), 403–10, on 407.

132. Rosenfeld, "The Art" (n.123), 36.

133. Arthur Rosenfeld and Deborah Poskanzer, "A Graph is Worth a Thousand Gigawatt-Hours," *Innovations* 4, no. 4 (2009): 57–79; recounted in the redoubtable Frank Trentmann, *Empire of Things: How We Became a World of Consumers, from the Fifteenth Century to the Twenty-First* (London: Allen Lane, 2016): 1475; and the excellent Alexander Madrigal, *Powering the Dream: The History and Promise of Green Technology* (Cambridge MA: DaCapo Press, 2011): 157–58.

134. Caroline Westfall, "Surviving the Squeeze, National Labs in the 1970s and 1980s," *HSNS* 38, no. 4 (2008): 475–78; Earl Hyde, "Andrew Sessler's LBL Directorship," *AIP Conference Proceedings* 351 (1996), 96.

135. Barry Casper "Physicists and Public Policy: The 'Forum' and the APS," *Physics Today* 27, no. 5 (1974), 31–37, on 33.

136. Cassidy, *A Short History* (n.58), 140.

such as minority employment and sexism. Die-hard radical Schwartz considered it an exercise in "co-optation."[137]

Forum members proposed a summer school dedicated to "reducing energy consumption at the point of use."[138] Such schools were a post-war institution. Outstanding young researchers would meet outside of the academic calendar to give their undivided attention to a specific problem.[139] Months before OPEC imposed an embargo, the APS Directorate agreed to fund three energy-centered summer studies. The first on energy demand, the second on reactor safety and superconductors, and the third on "technical aspects of energy conservation."[140]

These topics were agreed at a four-day meeting organized by Princeton's Frank von Hippel in Los Alamos (see figure 1). The term "conservation" was rapidly changed to "efficient utilization."[141] Any high school physics student could explain that energy was always conserved; it was efficiency that mattered—at least from a human perspective.[142] Von Hippel and others also agreed energy demand was primarily "a function of social and economic, not scientific, factors." So, as physicists, they would focus on *technological* efficiency, the domain in which they could claim some authority.[143] Funding came from the NSF, whose RANN program increasingly focused on energy, the APS, and the Electric Power Research Institute (EPRI), a consortium representing the interests of utility companies.[144]

Political moderation was baked into the project from the outset. Its aim was to explore approaches to energy saving that would not require "radical changes

137. Sarah Bridger, *Scientists at War: The Ethics of Cold War Weapons Research* (Cambridge, MA: Harvard University Press, 2015), 203; Mody, *Squares* (n.8), 2–3.

138. Casper, "Physicists" (n.135), 34.

139. Daniel Greenberg, *The Politics of Pure Science* (New York: New American Library, 1968), 127.

140. Forum on Physics and Society, "Newsletter: Council Approves Three APS-sponsored Energy Studies," *FPS Newsletter* 2, no. 3 (1973), 5.

141. AIP Archive, Box 8: Records of the American Physical Society (hereafter, Records), 1899–1989, Subgroup II, Series II, General Subject files. Robert Socolow Summer Study Proposals Generated by the APS Energy Study Planning Committee, Appendix C., Study on Physical Aspects of Energy Utilization, Oct 4, 1973.

142. AIP Archive: Box 8, Records, Letter from D. Fiske, Program Chairman, APS Topical Conference on Energy to Dr Abelson, at *Science* journal, Dec 28, 1973.

143. Golden, "APS Considers" (n.77), 70.

144. AIP Archive: Box 8: Records, Contracts and Grants: Summary as of 9/30/74. Electric Power Research Institute (EPRI, $25,000) and NSF ($61,500), 1.

FIGURE 1. The Forum on Physics and Society's Los Alamos Meeting. Source: Los Alamos Photo Laboratory, Neg. No. 73198-6. APS Archive.

in social or economic policy."[145] Forum members were also not particularly young, with a median age of forty-five. This was noted in a letter nuclear physicist Ken Krane wrote to Forum leaders. Krane complained that the organization failed to "deviate in any significant way from that of the APS leadership."[146] Its advisory board indeed had distinct establishment credentials, consisting of Rosenfeld's boss Alvarez, Alan Chynoweth of Bell Labs, James Comly a physicist from GE, not only a major utility company but also the nation's largest appliance manufacturer at the time. Comly managed GE's research lab in Schenectady, New York.[147]

What to make of utility company involvement? Most obviously, utilities stood to lose money if demand for energy actually decreased. As conservation

145. AIP Archive: Box 8, Records, The APS Energy Study Planning Committee, chaired by Jack Sandweiss (Yale) met at Los Alamos Laboratory, Aug 13–19, 1973, 3.

146. AIP Archive: Records, Box 26: Folder 5., Forum on Physics in Society, 1972–1973, 1/3, Letter from Kenneth Krane, LBL, to Earl Callen, American University Washington, Jun 12, 1973.

147. AIP Archive: Records, Box 8, photo 3; Redfield A. Proceedings of the Solar Heating and Cooling for Buildings Workshop, 24.

became an increasingly heavily promoted solution, a radical collective writing in *Science for the People* argued utility companies were among several special interests served by Federal government. Accordingly, they argued tweaking technological efficiency would not achieve much. Real reductions in energy use would require "the transformation of social and economic institutions."[148] Rather than being subsidized the collective demanded each corporation "pay to society the full economic value of the resources it exploits."[149] Boston SESPA's "energy group," led by David Jhirad, discerned a "blaming the consumer syndrome" in industry proposals. Their conservation initiatives, he noted, focused on consumer rather than industry. This, despite industry consuming 41 percent of the nation's total energy use. Industry was also treated better as a customer: federally set rate structures were regressive, charging large industrial consumers less per kilowatt than low-income consumers. Such rules, Jhirad argued, reflected the establishment's will to maintain a profitable and regressive "structural waste of energy."[150]

More recently, evidence of energy company subterfuge with regard to energy use, pollution, and climate change has been uncovered that affirms Jhirad's suspicions.[151] What then, we might ask, would energy policy look like if his views had been taken seriously at the time?

Jhirad's family came from Maharashtra, India. They were Bene Israel, members of a long-standing Indian Jewish community. He grew up in Shimla; he studied at St. Stephen's College in Delhi and Cambridge. He obtained his physics doctorate from Harvard University in 1972 with a thesis titled "The Direction of Time."[152] He had taught astronomy at Harvard but withdrew his academic labor on March 4, 1969, as part of a nationwide protest.[153] Lecturers

148. Jane Hill, Alex Szejman, and Mike Teel, "Ecology for the People," *Science for the People* 5, no. 1 (1973), 34–37, on 32.

149. Hill et al., "Ecology" (n.148), 36.

150. David Jhirad, "Energy," *Science for the People* 6, no. 1 (1974): 4–11, on 10.

151. Most recently: Geoffrey Supran, Stefan Rahmstorf, and Naomi Oreskes, "Assessing ExxonMobil's Global Warming Projections," *Science* 379, no. 6628 (2023): 1–13; Benjamin Franta, "Weaponizing Economics: Big Oil, Economic Consultants, and Climate Policy Delay," *Environmental Politics* 31, no. 4 (2022): 555–57; Emily Williams, Sydney Bartone, Emma Swanson, and Leah Stokes, "The American Electric Utility industry's Role in Promoting Climate Denial, Doubt, and Delay," *Environmental Research Letters* 17, no. 9 (2022): 094026.

152. Padu Padmanabhan, *First Fuel: India's Energy Efficiency Journey and a Radical Vision for Sustainability* (London: Pan Macmillan, 2021), 119.

153. Mark Oberle, "Four Professors Cancel Lectures in Protest of 'Misuse of Science," *Harvard Crimson*, Feb 28, 1969. www.thecrimson.com/article/1969/2/28/four-professors-cancel-lectures-in-protest

at MIT had gone on strike to oppose the military's tentacular involvement in university research, some of which was being used in Vietnam.[154] Later that year, Jhirad and his wife Susan, a literary scholar and feminist activist, plus a hundred others, occupied the dean's office.[155] They demanded an end to officer training and student evictions, as well as the establishment of an Afro-American Studies department.[156] Jhirad, of course, attended SESPA's Boston 1969 meeting and published regularly in *Science for the People*.

Jhirad's belief that utility companies had nothing to gain from actually saving energy needs to be tempered by the fact that engagement with industry was not unusual. Joseph Martin has shown how physicists had exchanged ideas and personnel with industrial labs throughout the twentieth century, and that the APS was never the bastion of basic science its founding statement (in 1899) had claimed. In the 1940s, the APS had founded a Division of Solid State Physics, with a strong industrial and commercial focus.[157] Moreover, companies such as Bell, RCA, Westinghouse, and GE had long made important contributions in both applied and basic physics.[158] Attesting to this, in 1972, solid state physicist Philip Anderson, who worked on condensed matter physics for Bell Labs, made an influential theoretical claim. He called for studies of "emergence," complex aggregates rather than isolated particles and their constituent subatomic matter.[159] He wrote "the more elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society."[160] Ouch!

Anderson's criticism somewhat mirrored the APS's concerns. Its 1974 annual meeting in Chicago included a "topical" spin-out conference for the first time titled "Physics Opportunities in Energy Problems."[161] Milan Fiske,

154. Dorothy Nelkin, *University and Military Research: Moral Politics at MIT* (Ithaca, NY: Cornell University Press, 1972), 62.

155. David Jhirad and Susan Jhirad, "Violence," *Harvard Crimson*, Apr 16, 1969. www.thecrimson.com/article/1969/4/16/violence-to-the-editors-of-the

156. Various, "An Open Letter from the Student Strikers of 1969," *Harvard Crimson,* Apr 11, 1989. www.thecrimson.com/article/1989/4/11/an-open-letter-from-the-student

157. Martin, *Solid* (n.43), 63–69.

158. Martin, *Solid* (n.43), 22.

159. Andrew Zangwill, *A Mind over Matter: Philip Anderson and the Physics of the Very Many* (Oxford: Oxford University Press, 2021), 246–49; Martin, *Solid* (n.43), 12–13.

160. Philip Anderson, "More Is Different: Broken Symmetry and the Nature of the Hierarchical Structure of Science," *Science* 177, no. 4047 (1973): 393–96, on 393.

161. James Golden "A Look at the Chicago Meeting," *Physics Today* 27, no. 1 (1973): 25–28, on 25.

another physicist from GE's Schenectady lab, was chair, and the meeting addressed areas of research where it was believed physics could improve energy supply, from liquified coal to mobile powerplants, fission, fusion, solar, catalysis, and hydrocarbon geophysics.[162] Gibbons, formerly of ORNL and now at the Federal Department of the Interior's Conservation Office, spoke on conservation. He described how the physicist's "way of thinking about things" now appeared "ubiquitous in energy conservation activities," and how physicists could now be found in fields from energy economics to energy analysis.[163] Increasingly, the applied and theoretical epiphanies of individual physicists accorded with the aims of the discipline's overseers, the NAS and APS. It was not simply a case of energy company capture but also long-held disciplinary mores.

RE-ENGINEERING

That year, Princeton hosted the energy efficiency summer school. Princeton was among several elite universities criticized for being a cog in the "military-industrial-academic" complex.[164] It was home to "engineering science," a term coined by former-dean Joseph Elgin to describe the technologically advanced engineering done at its Aerospace and Mechanical Sciences department.[165] The Institute for Defense Analysis (IDA), the organization that oversaw the JASONs, was next to the engineering department. From 1967 onward, this office became a focus of anti-war protestors. Student graphics engineer Steve Slaby and others demanded Princeton's engineers work for social progress rather than helping wage war.[166] Amid such changes, in what follows we trace the work of Princeton physicist Robert Socolow.

Socolow considered himself a "square," though one with radical credentials. He had interned at RAND in 1960, but a year later he assisted the

162. "Opportunities for Physics to Help Energy Research," *Physics Today,* no. 26, no. 12 (1973): 71; M. D. Fiske and W. W. Havens, eds. *Physics and the Energy Problem—1974: Proceedings of the American Physical Society Topical Conference on Energy* (New York: AIP/APS, 1974): 1–419.

163. Fiske and Havens, *Physics* (N.162), 15.

164. Stuart Leslie, *The Cold War and American Science: The Military-Industrial Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1994): 24n15.

165. Matthew Wisnioski, *Engineers for Change: Competing Visions of Technology in 1960s America* (Cambridge, MA: MIT Press, 2012), 107.

166. Wisnioski, *Engineers* (n.165) 106–9; Bridger, *Scientists* (n.137), 212–18.

anti-nuclear Pugwash Committee.[167] He graduated from Harvard with a doctorate in high-energy physics in 1964.[168] After time at Berkeley, where he recalled first encountering the counterculture, Socolow joined Yale's faculty, teaching theoretical and nuclear physics.[169] This career ended when he co-organized a campus "day of reflection" in March 1969, part of the "research stoppage" that had begun at MIT (Jhirad joined). Russian-speaking and well-traveled, in downing tools Socolow sought to reflect on the undesirable use of the "technology that our science has spawned."[170] That said, in correspondence he described himself as "responsible enough to irritate the more radical students."[171] He recalled Nobel-winning physicist and peace campaigner Owen Chamberlain telling him, "If you want to do something radical, make it look conservative."[172]

Socolow decided to become a professional environmentalist. This was encouraged by the NAS, whose Stanford summer meeting in 1969 had allowed him and Harte to identify as "geophysicians."[173] Their research on the Everglades Jetport had been rigorously physical. They calculated its possible effect on the water table. Higher-density saltwater would intrude into aquifers of lower-density fresh water. It would not only have destroyed Florida's cypress swamp but also its drinking water supply. They also calculated the prohibitive-energetic cost of generating the pressure needed for desalination.[174] The NAS supported further work on Jamaica Bay, an estuary threatened by a proposed extension of Kennedy International Airport.[175] Socolow's environmentalist turn was not taken lightly; he wrote of his unease

167. Socolow recalled dropping Linus Pauling at the dentist and picking Leo Szilard up from the airport. Robert Socolow, interview with Thomas Turnbull, November 2019.

168. Martha Davidson, "Portrait of Innovation: Robert H. Socolow," in *Inventing for the Environment*, ed. Arthur P. Modella, Joyce Bedi, 373–382 (Cambridge, MA: MIT Press: 2003).

169. Socolow, interview (n.167).

170. Robert Socolow, letter to Anne H. Cahn, 20 Nov 1970, https://archive.org/web/20130122051846/http://www.princeton.edu/mae/people/faculty/socolow/mit-letter-nov-1970.pdf; Robert Sokolow [sic], "Questioning Science," *Yale Daily News*, February 25, 1969, 2.

171. Robert Socolow, letter to Steve Fels, 22 Dec 1969. https://archive.org/web/20121102032609/http://www.princeton.edu/mae/people/faculty/socolow//steve-fels-dec-1970.pdf

172. Socolow, interview (n.167).

173. John Harte and Robert Socolow, *Patient Earth* (New York: Holt Rinehart and Winston, 1971), vii.

174. Harte and Socolow, *Patient Earth* (n.173), 270, 273.

175. Robert Socolow, "Failures of Discourse," in *When Values Conflict*, ed. Laurence Tribe, Corrine Schelling, and John Voss, 1–34 (Cambridge MA: American Academy of Arts and Sciences, 1976), 28.

in "abandoning the certainty of the Lorentz group and the frankness of the physics seminar for the imprecision of the salt marsh and the deviousness of the political compromise."[176]

THERMAL SIGNATURES

In 1972, Socolow moved to Princeton, where physicist George T. Reynolds had secured RANN funding for a Centre for Environmental Studies, supported by Goldberger, the physicist-environmentalist advocate whose views had so irked Forman.[177] Reynolds, a blast effects specialist at Los Alamos, directed Princeton's high-energy physics laboratory after the war, but was later drawn to environmental science after working on bio-luminescent dinoflagellates.[178] At Princeton, Socolow's environmental interests would center on energy.

Rather than an endangered environment, Socolow and colleagues studied a "planned unit development," a housing project in Twin Rivers, New Jersey. A local entrepreneur had begun transforming potato fields into three thousand seemingly identical homes in 1969, each fitted with the same appliances.[179] As people moved in, *Princeton Alumni Weekly* described how "a real-world laboratory was growing in Princeton's backyard."[180] Socolow's aim was to test the idea that efficiency gains in individual houses could be scaled up, creating aggregate savings. Socolow's team created three "highly instrumented townhouses," fitting them with anemometers, infrared scanners, oscilloscopes, and thermostats. These devices recorded the buildings' thermal properties and meteorological conditions. Appliances were monitored using an Esterline-Angus Data Acquisition System, a power meter relaying data to Princeton's engineering department.[181] In contrast to computer models, field

176. A set of constancies used in particle physics. Socolow, letter to Fels (n.171), 2.

177. Landon Jones, ed., "The University," *Princeton Alumni Weekly*, Feb 2, 1971, 3.

178. Sol Gruner, Pierre Piroué, and Robert Socolow, "Obituary: George T. Reynolds," *Physics Today* 58, no. 10 (2005): 102.

179. Richard Grot and Robert Socolow, "Energy Utilization in a Residential Community," in *Demand, Conservation, and Institutional Problems*, ed. Michael Macrakis, 483–98 (Cambridge, MA: MIT Press, 1974).

180. Florence Helitzer, "The Quality of Our Lives: A Sampling of What Princeton Professors Are Doing about It," *Princeton Alumni Weekly* Oct 30, 1973, 5–6.

181. Robert Socolow and Robert Sonderegger, *The Twin Rivers Program on Energy Conservation in Housing: Four Year Summary Report*, Centre for Environmental Studies, no. 32. NSF-RANN Contract 6-35758 (Princeton, NJ: Princeton University, 1976), 6.

measurement revealed houses marked by defects, leakages, and losses: distinct thermal "signatures."[182]

Worse still, as the houses were occupied, it appeared the same number of people in the same type of building could use twice as much energy. Physical improvements could go only so far in achieving savings. Behavior appeared the determining factor shaping energy demand. In a *New York Times* interview, Socolow put it simply: "the problem is not simple. Just adding more insulation is not going to solve the energy crisis."[183] Rather than scaling up savings, the unique thermal signatures of supposedly identical buildings had to be studied *alongside* the irregularities of human behavior. These lessons led Socolow to adopt the watchword "disaggregate!"[184] Through tailored "retrofits," Socolow's "house doctors" were able to reduce home heating use by as much as 67 percent through targeted insulation measures and behavior change.[185] Retrofitting became an applied field science in which the idiosyncrasies of buildings and their occupants became the objects of study.

REDEFINING EFFICIENCY

The Daily Princetonian documented how the energy crisis had unfolded on campus. The Federal fuel allocation program cut off gas supplies and limited fuel oil, delaying the semester's start. Dormitory thermostats were limited to 68° Fahrenheit, and offices and classrooms to between 60° and 65°. Nonetheless, the *Princetonian*'s editors breezily assured readers that "the university community has shown a remarkable degree of cooperation and good spirit."[186] That summer, Socolow, as PI of the efficiency study, welcomed attendees to Princeton. He was joined by SESPA founder Ross, and more senior physicists Kenneth Ford and Gene Rochlin, Daniel Harley of Sandia national lab, and

182. Socolow and Sonderegger, *Twin Rivers Program* (n.181), 162.

183. David Bird, "Energy in the Home Being Tested at Twin Rivers," *New York Times,* May 27, 1973, 49.

184. Robert Socolow, "The Coming Age of Conservation," *Annual Review of Energy* 2 (1977): 239–89.

185. Frank Sinden, "A Two-Thirds Reduction in the Space Heat Requirement of a Twin Rivers Townhouse," *Energy and Buildings* 1, no. 3 (1977): 243–60.

186. Editorial, "Bundle Up for Energy," *Daily Princetonian* 97, no. 124 (1973): 6.

FIGURE 2. The directors of the APS Summer Study. L–R: Robert Socolow, Dan Hartley, Marc Ross, Sam Berman. Source: Editorial, "Summer Group Focuses on Efficient Energy Use," *Physics Today*, no. 9. (1974): 75.

Sam Berman from California Tech. Rosenfeld, whom Socolow knew, was a leading participant (figure 2).[187]

Seventy physicists, chemists, regulators, and utility company and industrial lab employees attended the summer school. Core participants met at Princeton's eighteenth-century Nassau Inn to begin five weeks of study. Proceedings published a year later explained their intention had *not* been to "derogate *regulatory, economic,* or *persuasive* tools" to increase energy efficiency. To do so would have led them to encounter "problems of non-technical trade-offs," the kinds of thing economists or social scientists dealt with. Behavioral questions of substitution and preferences and other "psychological or socially determined" concerns were not their concern.[188] Instead, they focused on

187. Editorial, "Summer Group Focuses on Efficient Energy Use," *Physics Today* 27, no. 9 (1974): 75; on Ross, see Moore, *Disrupting* (n.44), 151; Socolow, interview (n.167).

188. Walter Carnahan, Barry Casper, Kenneth Ford, Andrea Prosperetti, Gene Rochlin, Arthur Rosenfeld, Marc Ross, Joseph Rothberg, George Seidel, and Robert Socolow, *Efficient Use of Energy: A Physics Perspective*, AIP Conference Proceedings 25 (New York: American Institute of Physics, 1975), 4–5; Robert Socolow, "Efficient Use of Energy," *Physics Today* 28, no. 8 (1975): 23–33.

"*technical* aspects" of energy use, where they believed they could make a practical contribution to the ongoing crisis.[189]

Core participants were briefed for ten days, primarily by industry representatives.[190] There was a cluster of electronics research and manufacturing organizations in New Jersey that some called the "Princeton Corridor." Bell, AT&T, and RCA's research labs were nearby, from which consumer appliances, from color television to microwaves, had emerged.[191] The industry briefing affirmed the school's focus on energy consumption via housing, automobiles, industry, combustion, windows.[192] Attendees modeled these as "simplified thermodynamic systems."[193] The resulting equations were then used to estimate the minimum energy needed to execute a given task. The idea was that minimizing "task energy" via increases to technical efficiency would conserve increments of available energy.[194] Overall, the group estimated that the United States consumed energy with an average efficiency of only 10–15 percent, a profligacy they later described as "not only wasteful, but inelegant."[195]

The school's major theoretical contribution was to redefine efficiency. The first law of energy dictates that energy is always conserved. This law can be presented as a ratio of input to output (η = energy transferred/energy inputted). This indicated the amount of energy *usefully* conserved. That is, in a form likely able to do subsequent work as opposed to energy unable to do so. In such measurements, an increase in efficiency increased the ratio of obtainable work. The ratio of energy transferred (*usefully* conserved) in a given conversion process increased. Defined this way, as had generally been the case since the discovery of thermodynamics in the mid–nineteenth century, increased efficiency did not mean *less* energy had been used overall, simply that the conversion produced more useful output.[196]

189. Carnahan et al., *Efficient Use* (n.188), 8–9.

190. Including staff from five utility companies, Carnahan et al., *Efficient Use* (n.188), vii–viii; AIP archive. Box 8: Records of the APS, 1899–1989, Subgroup II, Series II, General Subject files, 4. Letter from Socolow to Havens, Jun 28, 1974.

191. Stuart Leslie and Robert Kargon, "Electronics and the Geography of Innovation in Post-War America," *History and Technology* 11, no. 2 (1994): 217–31, on 218–10; on regional technology clusters see Mody, *Squares* (n.8), ch 2.

192. Martin, *Solid State* (n.43), 12.

193. Carnahan et al., *Efficient Use* (n.188), 16.

194. Carnahan et al., *Efficient Use* (n.188), 24.

195. Ibid., 9; on elegance see Stevens, "Fundamental" (n.18), 175–76, 181.

196. Ernst Berndt, "Aggregate Energy, Efficiency, and Productivity Measurement," *Annual Review of Energy* 3 (1978): 225–73, on 229; on nineteenth-century thermodynamics, Crosbie

First Law Efficiency:

$$\eta = \frac{\text{energy transfer achieved by a device or system}}{\text{energy input to device or system}}$$

Summer school attendees traced the "roots" of their redefinition to an 1878 paper by Yale physical chemist Josiah Willard Gibbs. In trying to make chemistry and thermodynamics commensurable, Gibbs had argued that "the comprehension of the laws which govern any material system is greatly facilitated by considering the energy and entropy of the system in the various states of which it is capable."[197] He thought the thermodynamic manipulation of chemical compounds should focus on the quality rather than the quantity (ratio) of energy in a given system. Measurement should differentiate between energy disqualified from use owing to entropy and energy remaining available for work. In advocating Gibbs's concept of "available energy" as a basis for measuring conservation, these physicists argued energy efficiency should be redefined so as to account for the *quality* of energy in a given system.[198]

In making their argument, criticism was leveled at the emerging field of energy economics, particularly the authors of a 1972 Stanford Research Institute (SRI) study, *Patterns of Energy Consumption in the United States*, who proposed measuring energy use in uniform British thermal units without reference to variations in quality.[199] Founded in 1946, the SRI was conceived as a conduit for commercial and state-driven research to take place at this particularly entrepreneurial university. By the 1960s, the SRI was a target for activists, who opposed its compromised "interdisciplinary" work.[200] Responding to the SRI's energy study, the physicists conceded that "questions of price, regulation, and acceptability are not emphasized in our reports," and so it was likely "analysis by social scientists" could "winnow further the ideas we have selected to present."[201] That is, they admitted their estimated efficiency savings might be tempered by economics and other behavioral sciences.

Smith, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain* (Chicago: University of Chicago Press, 1998).

197. Carnahan et al., *Efficient Use* (n.188), 4; Josiah Willard Gibbs, "III. On the Equilibrium of Heterogeneous Substances," *Transactions of the Connecticut Academy* 3 (1878): 108–248, on 108.

198. Carnahan et al., *Efficient Use* (n.188), 17–19.

199. Stanford Research Institute, *Patterns of Energy Consumption in the United States* (Washington, DC: USGPO, 1972).

200. Rebecca Lowen, *Creating the Cold War University: The Transformation of Stanford* (Berkeley: University of California Press, 1997), 113–19; Mody, *Squares* (n.8), 103–4.

201. Carnahan et al., *Efficient Use* (n.188), 16–17.

On the firmer ground of technicalities, the physicists' "second law efficiency" proposed that a given quantity of energy had a certain potential to do useful work. So, those seeking to save energy should try to execute a given task/process with the minimal expenditure of available/useful energy. Electricity generation, for example, conventionally requires the conversion of chemical energy to electrical energy via combustion. Heat is used to generate steam, which drives a turbine—whereas using a fuel cell to generate electricity will have a higher second law efficiency as this avoids the intermediary and irreversible combustion stage.[202] Energy conservation must take such *qualitative* differences in energy-conversion processes into account. Conservation could be pursued by assuring available energy was qualitatively matched to appropriate tasks: waste heat, a by-product of combustion, could be best used for low-temperature heating, for instance. Energy is always conserved, but its quality varies, and mismatches between quality and use result in irretrievable losses.

Second Law Efficiency:

$$\epsilon = \frac{\text{actual heat or work usefully transferred}}{\text{theoretical maximum heat or work usefully transferred}}$$

Considering energy in qualitative terms had accounting implications. First, it required the calculation of a theoretical *maximum* amount of energy that could be obtained from a given conversion process ("maximum possible work extracted from a given quantity of fuel"). Second, the *amount* of energy ("minimum work") required to complete a task needed to be estimated. *Dividing* the second figure by the first (ϵ = "actual heat or work usefully transferred"/"theoretical maximum heat or work transferable"), an alternative metric termed "Second Law Efficiency" could be reached that indicated the most energy-economical way, theoretically, to complete a task/process.[203] If second law efficiency could be increased, then more available energy would be conserved, and of use elsewhere or later. Accordingly, engineers should no longer try to maximize the ratio of inputted energy to outputted work. This may not save energy overall. Instead, they should minimize the use of available energy.

202. Socolow, "Efficient Use" (n.188), 29; Carnahan et al., *Efficient Use* (n.188), 31–32.
203. Socolow, "Efficient Use" (n.188), 26–27.

Redefining efficiency encouraged a reimagining of the sites of conservation. As the school's proceedings put it, "the viscoelastic flexing of rubber tires, the pyrolysis of fuel droplets, the gas discharge in fluorescent bulbs, the behavior of boundary layers at the surfaces of windows" could become sites of energy saving.[204] Thermal diodes, fluorescent lighting, insulating window coatings, and new conductive materials could markedly increase household energy availability. With around 60 million "dwelling units" in the United States, marginal efficiency increases were expected to lead to large aggregate savings.[205] Dynamotors, batteries, flywheels, and viscoelastic materials could improve "rubber-tired, internal combustion engine-powered" vehicles, which accounted for about 18.5 percent of total US energy consumption.[206] Improved gearing, engine technology, rolling resistance, and aerodynamics could reduce automobile energy demand by half.[207] However, strangely, despite US industry constituting 41 percent of the nation's energy use, no estimates for this sector were offered due to their supposedly "complex and varied" composition.[208] The omission is glaring. Was Jhirad right about the disingenuous role of industry involvement?

SECOND LAW EFFICIENCY

Second law efficiency affirmed the physicists' target: "Until recently, energy conservation meant conservation at the point of extraction; energy conservation in this sense motivated the organization of natural gas collection and huge capital investment in pipelines, as well as regulations on the maximum rate of withdrawal of oil from underground reservoirs."[209] For fifty years, this had meant petroleum conservation focused on the regulation of the oil industry's rate of extraction under the term "pro-rationing."[210] By contrast, as Jhirad feared, second law efficiency directed conservation to the *end* points of energy use. Rosenfeld affirmed that "reserves of energy created through conservation

204. Carnahan et al., *Efficient Use* (n.188), 22.

205. Ibid., 52.

206. Ibid., 7, 99.

207. Ibid., 121.

208. Ibid., 8, 18, 122. Additional studies looked into windows, and fuel emulsions that burnt despite containing less oil.

209. Ibid., 21.

210. Socolow, "Coming Age" (n.184), 242; Thomas Turnbull, "Toward Histories of Saving Energy," *Journal of Energy History* 4 (2020): 1–20, on 8.

do not lie in the ground; rather they lie in the *end uses* of energy."[211] It was, Rosenfeld went on, as if they had found a "huge oil and gas field buried in our cities (buildings), factories, and roads (cars)."[212] Consumers and their appliances, end uses, became the main focus of conservation efforts.

In redefining efficiency, these physicists reiterated ideas of some provenance in engineering. The debt was acknowledged in a cluster of citations and acknowledgments in the summer school's proceedings.[213] Mechanical engineer Joseph Keenan of MIT, previously a GE engineer, had taught thermodynamics since the 1930s. His long-standing textbook explained second law efficiency as a means to measure and improve the efficiency of steam turbines.[214] Notably, the only recommendation the physicists made with regard to industrial energy efficiency was that second law efficiency should be used to measure power generation; however, this was something long done and advocated by Keenan.[215] In 1972, colleagues of the septuagenarian Keenan presented a well-received paper at an NSF-funded conference on the energy crisis, held at MIT's recently founded Energy Laboratory.[216] Presented by co-author George Hatsopoulos, in line with second-law thinking, the paper argued recent events constituted an "entropy crisis"; the problem was not scarce energy but excessive entropy.[217]

Attendees were introduced to a follower of Keenan, Charles Berg, chief engineer at the Federal Power Commission (FPC), a promoter of the *technical* possibilities of using less energy.[218] Berg had contributed to the US Office of Emergency Preparedness study *The Potential for Energy Conservation* (1972), and voiced doubts about the economist's belief that increased fuel prices increased conservation savings. Surveying the United States, Berg identified numerous economically viable yet unexploited efficiency savings, despite energy's growing

211. Alan Meier, Janice Wright, and Arthur Rosenfeld, *Supplying Energy through Greater Efficiency: The Potential for Conservation* (Berkeley CA: University of California Press, 1983), viii.

212. Rosenfeld, "The Art" (n.123), 37.

213. Carnahan et al., *Efficient Use* (n.188) (n.202), 27n13, 14.

214. Ascher Shapiro, "Joseph H. Keenan," *Physics Today*, no. 11 (1977): 74–76.

215. Carnahan et al., *Efficient Use* (n.188) (n.202), 42.

216. Ernst Berndt, "Aggregate Energy, Efficiency, and Productivity Measurement," *Annual Review of Energy* 3 (1978): 225–73, on 231, n. 11.

217. Joseph Keenan, Elias Gyftopoulos, and George Hatsopoulos, "The Fuel Shortage and Thermodynamics—The Entropy Crisis," in Macrakis, *Energy* (n.175), 455–66.

218. Charles Berg, "Conservation in Industry," *Science* 184, no. 4134 (1974): 264–70.

cost.[219] In April 1974, he published *A Technical Basis for Energy Conservation* on behalf of the FPC. It argued energy scarcity was not solely a matter of price but also of fuel quality and environmental impact.[220] He briefed attendees on such "technical aspects," and the summer school's proceedings endorsed both Keenan and Berg.[221] Elsewhere, Berg noted that, with efficiency redefined, physicists could apply fundamental thermodynamic principles to the "mundane practices of every-day life."[222] Such work, he noted, would normally have been dismissed as something of mere commercial interest, "unlikely to stimulate greatly the curiosity of the young student physicist or engineer, or his professor."[223] However, the crisis and the credibility APS support afforded it had ennobled this prosaic task. As Socolow had hoped, a young scientist could now proudly identify as an "energy physicist."[224]

MEASUREMENT PROBLEMS

There were some criticisms of considering available energy as if it were a resource like any other. In a later survey of energy economics, historian of economic thought Philip Mirowski argued that any attempt to comprehensively measure second law efficiency for a given process required each act of energy conversion and all the other conversions this depends on to be accounted for. This, he believed, presented an insurmountable measurement problem: "one would rapidly learn that both the numerator and the denominator were so dependent on the particular context of use—that is, that the quantities involved are so path-dependent that the index has no meaning."[225] In practice, second-law accounting would be too simplified or prohibitively complicated.[226] Energy is a property of a system, defined by boundaries and

219. Charles Berg, "Potential for Energy Conservation in Industry," *Annual Review of Energy* 1 (1976): 519–34, on 529.

220. FPC, *A Technical Basis for Energy Conservation* (USGPO, Washington, DC), 1974, 2–3.

221. Carnahan et al., *Efficient Use* (n.188), 42.

222. Charles Berg, "Conservation via Effective Use of Energy at the Point of Consumption," in Macrakis, *Energy* (n.175), 467–82.

223. Berg, "Potential" (n.219), 521.

224. AIP Archive, Summer Study (n.141).

225. Philip Mirowski, "Energy and Energetics in Economic Theory: A Review," *Journal of Economic Issues* 22, no. 3 (1988): 811–30, on 819.

226. Isabelle Stengers, *Cosmopolitics I* (Minneapolis: University of Minnesota Press, 2010), 206.

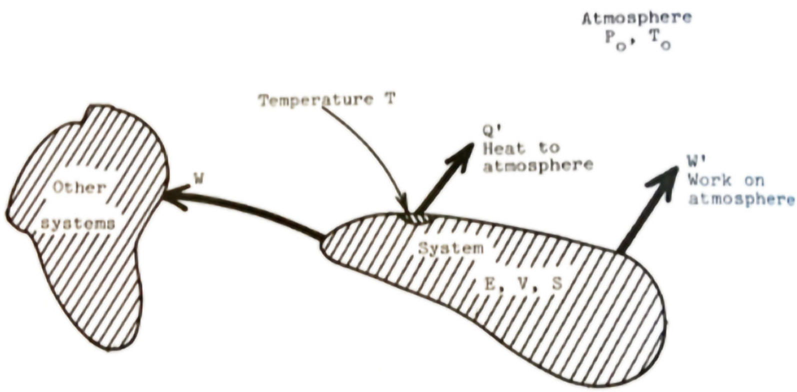

FIGURE 3. An energy system interacting with the atmosphere and transferring work (W = energy) to other systems: E = energy, S = entropy, V = volume, T_0 = atmospheric temperature, P_0 = atmospheric pressure. Source: Walter Carnahan et al., *Efficient Use of Energy*, fig. 2.4, p. 36.

connections to other systems; it is not an isolatable quantity.[227] Our physicists were aware of this, presenting a schematic alluding to a single system being nested in "other systems" (figure 3). Aware of such qualifications but seeking application amid a crisis, they had thought that of all Earth's accountants they were best placed to account for energy in a manner that cohered with thermodynamics.

Socolow had explained in a letter to project advisor Chauncey Starr of the EPRI that their aim had been to find "existence proofs"—evidence that energy use saving was not simply a matter of "prices and public attitudes" but demonstrable improvements in technical efficiency.[228] These proofs, unlike those of economists, stood up to physical inquiry. Unsurprisingly, then, attendees "strongly recommend[ed] that" their second law "formulation, or a similar one, be widely adopted by the scientific and technical community as a standard."[229] A wave of second law studies followed—including from Ross.[230] However, as economist Ernst Berndt had pointed out, while theoretically saved, available energy may be prohibitively

227. Keenan defined thermodynamics as "the relationship between heat, work, and the properties of *systems*," Joseph Keenan, *Thermodynamics* (New York: Wiley and Sons, 1941), 1.

228. APS archive, Box 8: Records, Letter from Socolow to Chauncey Starr, May 9 1974.

229. Carnahan et al., *Efficient Use* (n.188), 5, 42.

230. Berndt, "Aggregate" (n.216), 230–36; Marc Ross and Robert Williams, "The Potential for Fuel Conservation," *Technology Review* 79, no. 4 (1977), 48–57.

expensive or impossible to use in practice. Anticipating criticism, the summer schoolers had warned that "as physicists, we must think in in terms of what nature permits."[231]

FROM BUBBLES TO BUILDINGS

Socolow and Ross returned to distinguished careers at their respective universities. Rosenfeld returned to LBL, until inquiries from the CEC about California's energy use drew him back.[232] Within Sessler's Energy and Resources Group he taught an energy efficiency course. In 1975, he hosted a summer school, with attendees ranging from ecological economist Richard Norgaard to RAND's Ronald Doctor, and even a representative from Shell Oil. A banquet was laid on for distinctly un-groovy "guest of honor" Teller.[233] Sam Berman established an efficient lighting program in 1976.[234] Rosenfeld founded a Centre for Building Science, where he and others developed computer programs, DOE-1, DOE-2, and TWOZONE, to analyze building energy demand, evidence from which informed later Californian building codes.[235] He forged ties with the CEC, and in 1976 his group presented evidence that switching to more efficient appliances could save energy at such magnitude that a planned nuclear power plant in San Diego was no longer needed.[236] This helped institutionalize the idea that measurement could negate the need for new energy supply.

Modeling the thermal characteristics of buildings had parallels to particle analysis. Both analyzed complexes of energy and matter. Dean's words could

231. Carnahan et al., *Efficient Use* (n.188), 5.

232. Rosenfeld, "The Art" (n.123), 38.

233. Richard Norgaard, "Transdisciplinary Shared Learning," in *Sustainability on Campus: Stories and Strategies for Change*, ed. Peggy Barlett, Geoffrey Chase, 107–30 (Cambridge, MA: MIT Press); LBL archive, Container 1, Folder 2, June 1975 A. H. Rosenfeld, Univ. of California: LBL Summer Study and Institute, "The Efficient Use of Energy," 1975, 1; on Doctor, see Turnbull "California's Quandary" (n.72).

234. LBL Archive: Andrew M. Sessler, Research and Development Administrative Files, 1971–1980., Sam Berman, The LBL/University of California Lighting Program Overview, LBL, 1981.

235. James W. Cronin, ed., *Fermi Remembered* (Chicago: University of Chicago Press, 2004), 278; Rosenfeld and Poskanzer, "A Graph" (n.133), 64; Edward Dean and Arthur Rosenfeld, "Modelling Natural Energy Flow in Houses," *Energy and Buildings* 1 (1977): 19–26; Richard Hirsh, *Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System* (Cambridge, MA: MIT Press, 2002), 149.

236. LBL Archive, 1005—Energy Analysis, 1978–1979, Rosenfeld, A., Goldstein D., Lichtenberg A., Craig, P. Saving half of California's Energy and peak power in buildings and appliances via long-range standards and other legislation, 11.

have equally applied to particles, as "While we study components and systems as separate isolated subjects, in reality they are constantly working together and modifying the behavior of one another."[237] Anderson argued aggregate systems have complex and emergent properties. To understand the effect of efficiency increases at a meaningful scale remains exceedingly complex. The macrosocial implications of efficiency increases cannot be easily known. They involve innumerable path dependencies akin to those limiting second law efficiencies. Moreover, these physicists openly admitted their lack of authority regarding the social and behavioral determinants of energy use at any scale, while also acknowledging the vital importance of these factors.

If second law efficiency was not new, authoritative measurements of prosaic tasks were. In making them, these physicists had warned readers that their aim had not been "derogate regulatory, economic, or persuasive tools" to address demand beyond the technical domain, but to simply "present a unified overview of energy efficiency from the perspective of physics."[238] Others proved less cautious in this respect. Physicist-activist Lovins, now twenty-eight, wrote a piece in *Foreign Affairs* admitting that he "shamelessly recycled" others' work, including that of the summer school. He advocated a "soft path," a utopian energy future that made use of the physicists' estimates without qualification.[239] He popularized his argument in a book that used the school's findings to argue that, alongside efficiency measures, if energy prices were deregulated, a four-fold increase in national efficiency was possible.[240]

Lovins ignored that these physicists had made a qualified *technical* estimate. His work has since invited as much criticism as enthusiasm, but it has helped popularize the idea that energy services can be significantly decoupled from energy consumption.[241] Since the 1970s, analysts have persistently debated whether increased efficiency in fact leads to conservation savings or if the

237. Edward Dean, "Introduction to the 1975 Berkeley Summer Study," *Energy and Buildings,* no. 1 (1977): 7–10.

238. Carnahan et al., *Efficient Use* (n.188), 3.

239. Amory Lovins, "Energy Strategy: The Road Not Taken," *Foreign Affairs* 55, no. 1 (1976), 65–96, on 66n1.

240. Amory Lovins, *Soft Energy Paths: Toward a Durable Peace* (Cambridge, MA: Ballinger, 1977), 33.

241. Vaclav Smil "Soft Energy Illusions," in *Energy: Myths and Realities: Bringing Science to the Energy Policy Debate* (American Enterprise Institute, Washington, DC, 2010), 105–30; Helmut Haberl et al., "A Systematic Review of the Evidence on Decoupling of GDP, Resource Use and GHG Emissions," pt. 2, "Synthesizing the Insights," *Environmental Research Letters* 15 (2020): 1–42.

market response (lower costs) in fact offsets or increases demand.[242] Irrespective, by the 1990s, the idea that efficiency increases could slow growth in aggregate energy use had become a central pillar of international energy policy.[243] Today, in an age of human-induced climate change, the thermodynamically bound measurements these physicists insisted upon have been overwhelmed by cornucopian bromides that repackage corporate notions of efficiency.[244] That said, these physicists' achieved much when targeting specific systems. They invented efficiency standards, retrofits, and improved appliances[245]—all good starting points in what Socolow termed an "unending" struggle against entropy.[246]

CONCLUSION

Thirty-six years after his Weimar thesis, Forman made another influential contribution to the history of science. He described an "epochal shift" from the modernity-aligned pursuit of "science" to a postmodern concern with "technology," which he dated to around 1980. Explaining this, he wrote "the last place to look for transformative effects of this epochal shift in cultural values is the most characteristically modernist of our scientific enterprises, the high-energy, particle-physics accelerator laboratories."[247] This paper argues LBL was in fact one of the first places this shift could be discerned.[248] Rosenfeld, and others, developed a science of energy efficiency, with the aim of

242. Reinhard Madlener and Karen Turner, "After 35 Years of Rebound Research in Economics," in *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*, ed. Tilman Santarius, Hans Jakob Walnum, and Carlo Aall, 17–36 (Switzerland: Springer, 2016), 32.

243. Turnbull, "California's Quandary" (n.72); Thomas Turnbull, "'No Solution to the Immediate Crisis': The Uncertain Political Economy of Energy Conservation in 1970s Britain," *Contemporary European History* 31, no. 4 (2022): 570–92, on 591–92.

244. Mithra Moezzi, "Decoupling Energy Efficiency from Energy Consumption," *Energy & Environment* 11, no. 5 (2000): 521–37.

245. Harry Saunders et al. "Energy Efficiency: What Has Research Delivered in the Last 40 Years?," *Annual Review of Environment and Resources* 46 (2021): 135–65.

246. Socolow, "Coming Age" (n.184), 253.

247. Paul Forman, "The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology," *History and Technology* 23, no. 1 (2007): 1–152, on 11.

248. On periodisation, see Cyrus Mody, "Climbing the Hill: Seeing (and Not Seeing) Epochal Breaks from Multiple Vantage Points," *Science Transformed?: Debating Claims of an Epochal Break*, ed. Alfred Nordmann, Hans Radder, and Gregor Schiemann, 54–65 (Pittsburgh: University of Pittsburgh Press, 2011).

conserving energy. Was this the beginning of a postmodern energy-historical period, preoccupied with technologies rather than science? Perhaps so. In the late 1970s, DOE staff lamented using funds to work on efficient lightbulbs, technologies "which require as much marketing expertise as technical competence."[249]

The science of energy efficiency was arguably not as sublime as studying particulate matter, nor as Faustian as nuclear physics, yet for some there was a bigger plan for this "little science."[250] Truly saving energy meant radical change. Jhirad dismissed mainstream conservation as a trick, a guise to persuade consumers to make sacrifices that perpetuated a capitalist system "based on 'cheap' stolen energy" and designed only for "private profit." Real change would require "the redesign of society itself"—mass transit systems, transformed architecture, agriculture, lifestyles, and labor relations.[251] The moderate radicals had meant well, but their proximity to utility companies, consumer focus, and refusal to challenge industry seemingly demonstrated an acquiescence to a nascent neoliberalism.

In 1979, as Iran nationalized its oil, Anderson advised the APS that physicists still "continue[d] to be the professional community best qualified to advise and in some cases to work on this problem."[252] But changes were afoot. In the 1980s, even radical stalwart Jhirad conceded to working at Brookhaven, where he studied energy efficiency as a "bridge" to solar power in what was then called the developing world.[253] Another physicist clung on to the idea of conservation as a means to maintain US hegemony. In 1984, Teller seemingly feared a Soviet takeover in the Persian Gulf. He cast conservation as a means of "neutralizing the oil weapon."[254] Both perspectives pointed toward a growing recognition of

249. LBL Archive, Dr Andrew M. Sessler, Research and Development Administrative Files, 1971–1980., Container, 9., 1003-E&E Conservation: "DOE Labs may lose conservation research," *Energy Conservation Digest* 2., no. 13 (Jun 25, 1979): 6.

250. Physicist-historian Derek de Solla Price's term, APS archive, Box 8. Records:, Socolow, letter to Chauncey Starr, 9 May 1974, 1.

251. David Jhirad, "Energy," *Science for the People* 6, no 1. (1974): 4–11; David Jhirad, "Battling on Energy," *Science for the People* 8, no. 3 (1976): 32–33.

252. Philip Anderson, "Statement for the APS," *Newsletter of the Forum on Physics and Society* 8, no. 3 (1979): 4.

253. Editors, "Working with Energy Problems in Developing Countries," *Brookhaven Bulletin* 38, no. 27 (1984): 1.

254. Edward Teller, "Energy and Peace," in *To Promote Peace: U.S. Foreign Policy in the Mid-1980s*, ed. Dennis L. Bark (Stanford, CA: Hoover Institution, Stanford University Press, 1984), 69–82, on 80.

the power of other nations. Moreover, as market-based thinking found footholds across the world in this decade, our physicists' careful work was slowly replaced by more cornucopian claims that left economic and thermodynamic reality behind: even LBL staff now argued the price mechanism could almost indefinitely summon conservation savings from target systems.[255]

Today, with the crisis of anthropogenic climate change, dramatic reductions in fossil fuel energy are clearly needed. However, while the insights of those described here have been folded into energy policy in the United States and elsewhere, little effort is made to prove that energy efficiency increases, of which there is clear evidence, have decreased aggregate energy use.[256] Aggregate savings are abstractly assumed rather than accounted for. In part, this is because measurement at an appropriate scale is difficult. Anderson-like, a recent survey of forty years of research states that "the concept and metrics for energy efficiency become more difficult to define as systems boundaries increase and become more complex," and at larger scales "uncertainty prevails."[257] Do the laws governing isolated systems hold at a planetary scale? Perhaps efficiency increases have emergent effects in a domain ruled by subjectivity, contingency, and disorder?[258] If efficiency gains are to save energy at the necessary scale, the problem must be approached with renewed specificity, ambition, and radicalism.

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255. As "energy prices rise, new measures will become economic," Alan Meier, "Conservation Will Always Be with Us," *Energy* 6, no. 7 (1981): 585–89, on 588.

256. Paul Brockway et al., "Energy Efficiency and Economy-Wide Rebound Effects: A Review of the Evidence and Its Implications," *Renewable and Sustainable Energy Reviews* 141 (May 2021): 1–20.

257. Saunders et al., "Energy Efficiency" (n.245) 140–41.

258. In the 1980s, particle physics "dissolved into a multiplicity of competing narratives." Stevens, "Fundamental" (n.18), 197.