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Lessons From the Past for Assessing Energy Technologies for the Future

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ABSTRACT

Addressing climate change will require the successful development and implementation of new energy technologies. Such technologies can, however, pose novel and uncertain hazards. Furthermore, the process of energy innovation is technically difficult and occurs in the face of powerful forces hostile to new technologies that disrupt existing energy systems. In short, energy innovation is difficult and hazardous but essential. This Article presents case studies of three existing energy technologies to obtain insights in anticipating technological change, managing uncertain hazards, and designing appropriate laws and policies. The Article then applies these insights to a varied sample of emerging energy technologies. Ultimately, laws and policies should distinguish between new energy technologies according to (1) their state of readiness, (2) their potential to complement or disrupt existing energy infrastructures, and (3) the possible hazards associated with their full-scale deployment.

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INTRODUCTION

New technologies often pose uncertain hazards and develop in unpredictable ways. Such difficulties complicate the effective management of emerging technologies. This is especially true for new energy technologies, which are essential for tackling some of the world's greatest challenges, such as climate change and international development. Humanity's track record of encouraging new energy technologies while managing their risks is decidedly mixed. Some energy technologies have languished for lack of sufficient financial backing. Others have enjoyed commercial success and yet created serious environmental problems. Seeking to learn from these experiences, this Article presents case studies of existing energy technologies with the aim of better managing emerging energy technologies.

Part I of the Article provides a background on technology assessment. Differences in the innovation process for energy technologies as compared to other technologies have significant implications for energy innovation policy. Part II of the Article examines three existing energy technologies: corn-based ethanol, hydraulic fracturing, and nuclear energy. These case studies offer lessons in anticipating technological change, managing uncertain hazards, and designing appropriate laws and policies while incorporating public input. Part III applies these lessons to a sampling of emerging energy technologies: methane hydrates, advanced biofuels, and nanotechnology in solar panels. These three technologies are in different stages of development and have varying characteristics, hazards, and uncertainties. Ultimately, in designing law and policy to encourage innovation in the development of such technologies and to manage risk, it will be useful to distinguish between new energy technologies according to (1) their state of readiness, (2) their potential to complement or disrupt existing energy infrastructures, and (3) the possible hazards associated with their full-scale deployment.

I. TECHNOLOGY ASSESSMENT

A. Considerations in Technology Assessment

New technologies can have vast and unanticipated effects that make them challenging to manage. At the core of this challenge is the fundamental dilemma of technology control. When a technology is in its embryonic phase, there is often little information regarding its possible social and environmental consequences. Yet, once such information becomes available, the technology has often become too well established to be adequately controlled.[1] Moreover, contrary to popular understandings, technology typically does not develop in a predictable and linear manner, but instead through interactive, iterative, and unsystematic processes.[2] Furthermore, a variety of actors make technology-related decisions regarding research funding, investment in new technologies, and technology deployment.[3] These decisions, which have widespread effects, often lie beyond the public sphere. Law and other forms of governance can guide such decisions but more often than not struggle to keep pace with technological change.[4]

Despite the uncertainties that may surround a new technology, we often have reasonable suspicions as to what some of its hazards might be. As early as the late 1800s, for example, scientists recognized that fossil fuel combustion could contribute to a warmer climate.[5] Likewise, prior to the commercialization of nuclear power, scientists and citizens expressed concerns regarding the release of radiation.[6] Available information and reasonable hypotheses, even if they are limited, can inform oversight of new technologies.

Various legal and policy tools, moreover, can facilitate prediction and detection of the consequences of technological change. For example, mandatory information disclosure can enable identification of adverse effects. Technology assessments and futuring analyses can help society anticipate technological developments and their ramifications.[7] Environmental impact assessments can direct attention to possible environmental effects. Life cycle assessments can generate a more holistic understanding of the environmental impacts of a new technology by considering energy use, resource requirements, waste generation, and even social effects.[8]

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[1] DAVID COLLINGRIDGE, THE SOCIAL CONTROL OF TECHNOLOGY 16–19 (1980).

[2] *See* Stephen J. Kline, *Innovation is Not a Linear Process*, RESEARCH MANAGEMENT, March–April 1985, at 36.

[3] *See* ALBERT C. LIN, PROMETHEUS REIMAGINED: TECHNOLOGY, ENVIRONMENT, AND LAW IN THE TWENTY-FIRST CENTURY 7 (2013).

[4] The Coordinated Framework for the Regulation of Biotechnology is sometimes cited as an example of the shortcomings involved in trying to adapt existing law to new technology. *See* Coordinated Framework for Regulation of Biotechnology, 51 Fed. Reg. 23,302 (June 26, 1986); Gregory N. Mandel, *Gaps, Inexperience, Inconsistencies, and Overlaps: Crisis in the Regulation of Genetically Modified Plants and Animals*, 45 WM. & MARY L. REV. 2167, 2236–38 (2004).

[5] Julia Uppenbrink, *Arrhenius and Global Warming*, 272 SCIENCE 1122 (1996) (noting also that scientists did not fully appreciate the extent of the warming to come).

[6] *See infra* Part II.C.

[7] *See* LIN, *supra* note 3, at 16–18, 25.

[8] *See* NAT'L RISK MGMT. RESEARCH LAB., U.S. ENVTL. PROT. AGENCY, LIFE CYCLE ASSESSMENT: PRINCIPLES AND PRACTICE 7–8 (2006), *available at* http://www.epa.gov/nrmrl/

Naturally, new technologies do not develop in a legal vacuum. The U.S. Congress, the executive branch, and the courts are all keenly interested in technology development and management. New technologies may be governed by existing legal regimes, or such regimes may be adapted to govern new circumstances.[9] Common law tort doctrines operate as a backstop to regulation by threatening to impose liability for the adverse consequences of new technologies.[10] Intellectual property law and tax codes, moreover, provide incentives or disincentives for new technologies. In the energy sector specifically, incentives such as research grants, subsidies, tax credits, and renewable portfolio standards are important tools that encourage technology innovation and dissemination. Together, these various legal instruments help to shape the environment in which new technologies develop.

Technology's influence is pervasive, affecting not only the specific markets and industries in which it is deployed but also people's lives and interests, and society and its institutions more generally. Given the breadth and depth of this influence, strong instrumental, normative, and substantive rationales support direct public participation in the assessment and management of new technologies.[11] Instrumentally, public participation can facilitate support for innovation and acceptance of new products.[12] Normatively, public participation reflects principles of democratic governance, social justice, and equality by empowering citizens to actively engage in the management of powerful technological forces.[13] And as a substantive matter, public participation can yield useful insights and suggestions. Public participation also infuses the policymaking process with community values and preferences, such as tolerance for risk and uncertainty, desire for change, and willingness to make tradeoffs.[14]

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std/lca/lca.html (follow "LCA 101 document (PDF)" hyperlink); *see also* Jeroen B. Guinée et al., *Life Cycle Assessment: Past, Present, and Future*, 45 ENVTL. SCI. TECH., 90, 90–93 (2011).

[9] *See supra* note 4.

[10] For new technologies involving abnormal risks, courts may apply strict liability. *See* Ind. Harbor Belt R.R. Co. v. American Cyanamid Co., 916 F.2d 1174, 1176–77 (7th Cir. 1990) (discussing Guille v. Swan, 19 Johns. 381 (N.Y. Sup. Ct. 1822), in which a hot air balloonist was held strictly liable for damages to a garden caused by a crowd that sought to rescue him when he landed).

[11] Andy Stirling, *Opening Up or Closing Down? Analysis, Participation and Power in the Social Appraisal of Technology*, *in* SCIENCE AND CITIZENS: GLOBALIZATION & THE CHALLENGE OF ENGAGEMENT 218, 220–23 (Melissa Leach et al. eds., 2005).

[12] *Id.* at 220–22.

[13] *Id.* at 220–21; *see also* Kristin S. Shrader-Frechette, *Evaluating the Expertise of Experts*, 6 RISK: HEALTH, SAFETY & ENV'T 115, 117 (1995) (arguing for the right of public participation in risk assessments because they have consequences for public welfare).

[14] *See* Stirling, *supra* note 11, at 222 (discussing substantive rationale for public participation and explaining that such rationale relates to whether "technology choices are actually congruent with, and authentically embody, diverse social knowledges, values and meanings").

B. Energy Technology Innovation

1. The Energy Innovation Process

While the innovation process described above generally holds for energy technologies, energy innovation also possesses certain distinct features. As is the case with innovation in other sectors, energy technology innovation consists of multiple interrelated stages, including fundamental research, applied research, development, demonstration, and deployment.[15] Public investment in energy technology innovation—particularly in fundamental research—is often justified in terms of pollution and national security externalities, high barriers to entry, long time horizons, and specialized capabilities that the private sector may lack.[16] As an innovation approaches deployment and investment prospects begin to rise, it is typical for private sector involvement to increase and public sector involvement to decrease.[17]

Compared to innovation in other areas, the energy innovation process tends to be more protracted. The so-called valley of death describes the struggle of some innovators to obtain funding to advance a technological breakthrough from the research stage to proof of concept, and ultimately to full-scale commercialization.[18] This struggle, while not unique to the energy sector, is particularly pronounced for energy technologies because their development faces substantial risks while also consuming large amounts of capital and time.[19] The risks associated with energy technologies are manifold, including technical, economic, regulatory, and market uncertainties, as well as patentability concerns.[20] Of particular concern is the volatility of energy prices,

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[15] Kelly Sims Gallagher et al., *Energy-Technology Innovation*, 31 ANN. REV. ENVTL. RESOURCES 193, 200–06 (2006); *see also* RICHARD K. LESTER & DAVID M. HART, UNLOCKING ENERGY INNOVATION: HOW AMERICA CAN BUILD A LOW-COST, LOW-CARBON ENERGY SYSTEM 32–34 (2012). These stages are not strictly related in a linear manner, as dynamic feedbacks occur between different stages. Gallagher et al., *supra,* at 200. *See generally* CHARLES WEISS & WILLIAM B. BONVILLIAN, STRUCTURING AN ENERGY TECHNOLOGY REVOLUTION 16–28 (2009) (discussing theories of innovation).

[16] Gallagher et al., *supra* note 15, at 202–03. For example, U.S. government laboratories gained special expertise in atomic energy research during World War II, and this expertise proved critical to the development of civilian atomic energy applications. *See infra* Part II.C.

[17] Gallagher et al., *supra* note 15, at 200, 202.

[18] JESSE JENKINS & SARA MANSUR, BREAKTHROUGH INST., BRIDGING THE CLEAN ENERGY VALLEYS OF DEATH 5–6 (2011); *see also* LESTER & HART, *supra* note 15, at 101.

[19] *See* JENKINS & MANSUR, *supra* note 18, at 7–8, 13–14 (describing "technological valley of death" and "commercialization valley of death").

[20] *See* LESTER & HART, *supra* note 15, at 101–02 (noting technical, economic, regulatory, and market uncertainties); WEISS & BONVILLIAN, *supra* note 15, at 31 (explaining that private investors will not be able to appropriate all the gains that accrue to society from investments in energy innovation); *see*

which contributes to market uncertainty and discourages long-term investment in alternative energy technologies.[21] Venture capitalists are not likely investors in energy innovation because they focus on modest investments that involve higher potential profit margins, lower product development costs, and shorter timeframes.[22] Project financiers who do have the substantial capital that energy technologies often require are reluctant to back high-risk projects, such as those involving energy technologies.[23]

Several features of energy systems and markets compound these difficulties and favor incumbent technologies over new ones. Energy generation and delivery rely on extensive and long-lived infrastructure that turns over slowly.[24] In addition, because energy systems are often complex, large-scale technology adoption may require multiple innovations.[25] These systems are owned and operated by powerful incumbent firms that have benefited from substantial subsidies.[26] Furthermore, these systems exist within a society that takes for granted abundant and inexpensive energy.[27] The consequence of costly and entrenched infrastructure, complex systems, market dominance, and social expectations is lock-in—a condition in which the status quo is especially difficult to dislodge.[28] At the same time, new energy technologies rarely introduce radical new functionalities with immediate market appeal, in contrast to smartphones and other digital innovations.[29] The average consumer is unlikely to perceive electricity generated from wind or solar power as materially different

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also Zhongming Wang & Alan Krupnick, *A Retrospective Review of Shale Gas Development in the United States: What Led to the Boom?*, RESOURCES FOR THE FUTURE, Apr. 2013, at 3 ("[I]t is difficult to keep new technologies proprietary in the oil and gas industry, and few technologies are patentable or licensable.").

[21] WEISS & BONVILLIAN, *supra* note 15, at 7.

[22] *See* LESTER & HART, *supra* note 15, at 102–04; JENKINS & MANSUR, *supra* note 18, at 7–8, 13–14; U.S. GOV'T ACCOUNTABILITY OFFICE, GAO-12-112, DEPARTMENT OF ENERGY: ADVANCED RESEARCH PROJECTS AGENCY—ENERGY COULD BENEFIT FROM INFORMATION ON APPLICANTS' PRIOR FUNDING 14–16 (2012).

[23] *See* LESTER & HART, *supra* note 15, at 101–04; JENKINS & MANSUR, *supra* note 18, at 7–8, 13–14 (explaining that "[t]raditional venture capitalists are accustomed to investing in demonstration and pilot projects, but only at much smaller scales" and that traditional project financiers "have a much lower tolerance for risk than venture capitalists and are only willing to back later iterations of innovative technologies, where commercial validity has already been proven").

[24] *See* LESTER & HART, *supra* note 15, at 26; Gallagher et al., *supra* note 15, at 225.

[25] LESTER & HART, *supra* note 15, at 26.

[26] *See id.* at 35; WEISS & BONVILLIAN, *supra* note 15, at 32, 41.

[27] *See* WEISS & BONVILLIAN, *supra* note 15, at 28.

[28] Joseph P. Tomain, *"Our Generation's Sputnik Moment": Regulating Energy Innovation*, 31 UTAH ENVTL. L. REV. 389, 399–400 (2011).

[29] *See* WEISS & BONVILLIAN, *supra* note 15, at 15.

from electricity generated from fossil fuels.[30] In this "toughest kind of innovation environment," new players "face[] stringent, non-negotiable requirements on cost, quality, and reliability from the outset—along with competition from entrenched interests with deep connections . . . ."[31]

2. Implications for Government Support

The entrenched nature of existing energy systems has important implications for government's role with respect to new energy technologies. Dominated by economically and politically powerful actors, existing energy systems possess substantial inertia and pose significant barriers to entry. Industry and regulators "have developed a mutually supportive regulatory structure dedicated to promoting energy production," and consumers have developed living patterns dependent on cheap and reliable energy.[32]

Technologies that threaten to disrupt these systems will encounter resistance from incumbent parties that may take various measures to defend their interests. For example, incumbents may manipulate patents to stymie technology development and competition, fund research to identify potential hazards of emerging technologies, advocate regulation of potential rivals, or lobby against government support.[33] These efforts to suppress disruptive technologies are likely to occur even if new technologies offer prospective societal benefits.

Indeed, the obstacles to bringing new energy technologies to market and overcoming barriers to entry have created a "substantial backlog of energy technolog[ies] at various stages of readiness."[34] These include some technologies that require further basic research (such as fusion), others approaching the demonstration stage (such as enhanced geothermal), and still others technically ready to deploy (such as solar).[35] Overall, private investment in energy research

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[30] *See* VICKI NORBERG-BOHM, THE ROLE OF GOVERNMENT IN ENERGY TECHNOLOGY INNOVATION: INSIGHTS FOR GOVERNMENT POLICY IN THE ENERGY SECTOR 12 (Oct. 2002) (working paper), *available at* http://live.belfercenter.org/files/rolegovt.pdf (suggesting that government support may be especially crucial for such commodity goods).

[31] LESTER & HART, *supra* note 15, at 35; *see* WEISS & BONVILLIAN, *supra* note 15, at 14 (contending that political and public support for entrenched energy technologies "makes energy a different problem for our innovation system than others we have been confronting in recent decades").

[32] Tomain, *supra* note 28, at 391.

[33] *See* Benjamin K. Sovacool, *Placing a Glove on the Invisible Hand: How Intellectual Property Rights May Impede Innovation in Energy Research and Development (R&D)*, 18 ALB. L.J. SCI. & TECH. 381, 414–23 (2008) (discussing techniques of patent suppression, warehousing, and use of patents to block other firms from entering the market).

[34] WEISS & BONVILLIAN, *supra* note 15, at 29.

[35] *Id.*

and development lags significantly behind investment levels in other fields,[36] a shortfall that justifies government support for energy technologies beyond basic research. This support may take the form of direct participation in demonstration projects, such as the nuclear reactor demonstration projects that were pivotal to establishing the nuclear industry.[37] Government support also may include loan guarantees, insurance, and other financial tools to reduce the perceived risks of energy investments.[38] And it may involve new forms of support, such as the Advanced Research Projects Agency-Energy (ARPA-E), which provides funding to foster transformational technological advances that are too risky to attract private investment.[39]

Generally, disruptive technologies will warrant greater government support, particularly if these technologies promise benefits that market dynamics may overlook. Conversely, complementary technologies largely will warrant greater government scrutiny. Various energy technologies deployed in recent years illustrate the distinction between complementary and disruptive technologies. Hydraulic fracturing has dramatically transformed the American economy and rural communities over the last decade but is relatively undisruptive from the standpoint of existing energy systems.[40] The technique has been integrated quite readily into existing production systems, and it generates fossil fuels—natural gas and petroleum—that were already in widespread use. Accordingly, the technique arguably merits greater oversight than it has received. In comparison, corn ethanol is somewhat more disruptive. It introduces a new fuel type that directly competes with the dominant vehicle fuel, gasoline.[41] At the same time, corn ethanol can be integrated into existing fuel delivery systems (up to a limit), and its production relies heavily on fossil fuels. Far more disruptive are solar, wind, and nuclear energy. Each of these energy generation technologies directly competes with existing fossil fuel industries and would displace them if successful. This last group of technologies most warrants government support in demonstration projects, and even

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[36] JENKINS & MANSUR, *supra* note 18, at 9; *see also* LAURA DIAZ ANADON ET AL., TRANSFORMING U.S. ENERGY INNOVATION 61–62 (2011); LESTER & HART, *supra* note 15, at 103.

[37] *See* GEORGE T. MAZUZAN & J. SAMUEL WALKER, CONTROLLING THE ATOM: THE BEGINNINGS OF NUCLEAR REGULATION 1946–1962, at 21 (1984).

[38] *See* JENKINS & MANSUR, *supra* note 18, at 10–11, 16; *see also* Gallagher et al., *supra* note 15, at 203.

[39] 42 U.S.C. § 16538(c) (Supp. 2012); U.S. GOV'T ACCOUNTABILITY OFFICE, GAO-12-112, DEPARTMENT OF ENERGY: ADVANCED RESEARCH PROJECTS AGENCY—ENERGY COULD BENEFIT FROM INFORMATION ON APPLICANTS' PRIOR FUNDING 14–16 (2012); *see also* ANADON ET AL., *supra* note 36, at 37–41 (discussing various U.S. energy innovation institutions).

[40] *See infra* Part II.B.

[41] *See infra* Part II.A.

commercialization, should policymakers find adoption of these technologies desirable.

Public support for specific technologies sometimes provokes the objection that the government is unfairly picking winners.[42] One formulation of this objection counsels that "government should set the performance goals, but should avoid . . . picking which specific technologies should be developed to achieve those goals."[43] To be sure, the federal government has a mixed record in sponsoring new energy technologies, and large public expenditures can become a means of distributing political favors.[44] There are ways to insulate the process from inappropriate pressures, however. At the research and development phase, government can hedge its bets amid uncertain prospects for success by supporting a wide range of emerging technologies.[45] Individual failures at this stage do not necessarily reflect a flawed approach, as successful innovation requires acceptance of risk.[46] In addition, government can institute measures to guide funding decisions, such as establishing clear criteria for selecting projects, employing a transparent and competitive selection process, and appointing independent experts to participate in the process.[47] Ultimately, however, picking winners makes sense if it means that the government is spending its limited resources wisely and supporting those technologies that are more likely to achieve desired goals.[48]

C. Implications for Energy Technology Assessment

The barriers to energy innovations have important implications not only for public investment but also for energy technology assessment and the management of potential hazards associated with energy innovations. Although the dilemma of technology control remains relevant, the slower pace of innovation in the energy sector reduces the severity of the dilemma. Thanks to the lead time necessary to develop and deploy energy technologies, changes in energy

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[42] *See* Jim Watson, *Technology Assessment and Innovation Policy*, *in* ENERGY FOR THE FUTURE: A NEW AGENDA 123, 126–27 (Ivan Scrase & Gordon MacKerron eds., 2009) (recounting such views).

[43] Gary E. Marchant, *Sustainable Energy Technologies: Ten Lessons from the History of Technology Regulation*, 18 WIDENER L.J. 831, 836 (2009).

[44] *See* JOHN M. DEUTCH, THE CRISIS IN ENERGY POLICY 118–23 (2011) (discussing Department of Energy initiatives in nuclear power, synthetic fuels, and other areas).

[45] *See* NORBERG-BOHM, *supra* note 30, at 16.

[46] *See* ANADON ET AL., *supra* note 36, at 67; Watson, *supra* note 42, at 127.

[47] *See* DEUTCH, *supra* note 44, at 129–30; Hilary Kao, *Beyond Solyndra: Examining the Department of Energy's Loan Guarantee Program*, 37 WM. & MARY ENVTL. L. & POL'Y REV. 425, 500–01, 504 (2013).

[48] *See* Watson, *supra* note 42, at 127–30.

systems in the near term—including environmental improvements—will come primarily from technologies that already exist.[49] In some instances, these technologies have been studied substantially. Although scientists may not have uncovered the full extent of hazards associated with such technologies, they have identified many of those hazards. Policymakers and the public can then use this knowledge to decide how to proceed. As Part II discusses, corn ethanol, hydraulic fracturing, and nuclear power all exemplify currently utilized energy technologies whose associated risks are fairly well known because the technologies have been available for some time.

Further into the future, emerging energy technologies such as advanced biofuels, methane clathrates, and nanotechnology are poised to play significant roles. The long lead time to bring these technologies to market will allow for opportunities to begin assessing their health, environmental, and other consequences and to seek public input regarding these technologies' acceptability. Early assessment of potential hazards can guide investments in research and development, and promote wise and informed technology management.

Effective technology assessment should seek input from a wide range of stakeholders, including the public, in the energy innovation process. On a daily basis, much of the energy system is invisible to the public. Consumers may take electricity for granted—except when an outage makes it unavailable—and are often unaware of its source. At the same time, energy technologies affect society in many ways, not only through their effects on the environment but also through their impacts on economic development, work organization, transportation systems, and the like. These effects may lead to public controversy, as has long been the case for nuclear energy and is increasingly so for hydraulic fracturing today.

Controversy has often accompanied decisions regarding the siting of energy facilities,[50] but public input should not be limited to that context. The public should have an opportunity to participate in fundamental decisions regarding energy policy as well. Granted, public participation may be of limited utility when commercialization of a technology is distant,[51] and laypersons

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[49] LESTER & HART, *supra* note 15, at 27.

[50] *See, e.g.*, Patrick Devine-Wright, *From Backyards to Places: Public Engagement and the Emplacement of Renewable Energy Technologies*, *in* RENEWABLE ENERGY AND THE PUBLIC: FROM NIMBY TO PARTICIPATION 57 (Patrick Devine-Wright ed., 2013).

[51] *See* Rob Flynn et al., *The Limits of Upstream Engagement in an Emergent Technology: Lay Perceptions of Hydrogen Energy Technologies*, *in* RENEWABLE ENERGY AND THE PUBLIC, *supra* note 50, at 245, 251–54 (noting reluctance by people to make unequivocal statements about emerging technologies in the absence of direct experience with them).

may have difficulty grappling with technical and complex matters.[52] But in some instances, public participation can guide the expenditure of public resources and identify potential concerns for developers to keep in mind. In one interesting but rather simple experiment in seeking public input, ARPA-E asked the public to help choose promising energy startup companies to participate in a summit that would showcase their technologies.[53] Efforts in other countries to solicit public input have involved public workshops aimed at identifying preferences regarding national energy policy.[54] These examples suggest that public input may be most useful when providing general direction on energy policy or when technologies are sufficiently concrete to allow the public to judge tradeoffs between costs, benefits, and other relevant factors.

II. EMERGING ENERGY TECHNOLOGIES OF THE PAST

Although advances in energy technology can occur at all stages of the energy cycle (supply, distribution, and use), technology breakthroughs in supply tend to attract the most attention. Energy supply technologies often have dramatic effects and arguably require the most oversight, making them a suitable focus for discussion.[55] The three energy supply technologies considered in this Part—corn ethanol, hydraulic fracturing, and nuclear power—all established a significant presence in an era dominated by conventional fossil fuels. Accordingly, these case studies may offer important lessons for the development and management of emerging energy technologies to come.

A. Corn Ethanol

Corn ethanol has become an important vehicle fuel notwithstanding its dubious benefits and its detrimental effects on food supplies and the environment. The long history of official support for corn ethanol highlights the danger that politically powerful lobbies may distort or capture energy policies. This history also illustrates the feasibility of identifying many adverse conse-

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[52] *Id.* at 246.

[53] *See* Michael Hess, *America Chooses the Next Top Energy Innovator*, ENERGY.GOV (Feb. 10, 2012, 1:00 PM), http://energy.gov/articles/america-chooses-next-top-energy-innovator.

[54] *See, e.g.*, Peta Ashworth et al., *Turning the Heat On: Public Engagement in Australia's Energy Future*, *in* RENEWABLE ENERGY AND THE PUBLIC, *supra* note 50, at 131; Sigrid Stagl, *Multicriteria Evaluation and Public Participation: The Case of UK Energy Policy*, 23 LAND USE POL'Y 53 (2006).

[55] *Cf.* LESTER & HART, *supra* note 15, at 99, 143 (explaining the importance of innovation in low-carbon energy generation).

quences of energy technologies in advance. Incorporating such knowledge into the making of policy and law will be critical for the successful management of emerging energy technologies in the future.

Sometimes touted as an alternative to fossil fuels,[56] ethanol hardly represents a revolutionary technology. Indeed, ethanol and other plant-based fuels were used in early internal combustion engines.[57] Gasoline eventually became the predominant vehicle fuel source, however, thanks to its low cost and widespread availability.[58] Compared to gasoline, ethanol contains only about two-thirds as much energy per unit volume.[59] Ethanol also has the disadvantage of being corrosive, a characteristic that limits the amount of ethanol that can be blended with gasoline and distributed via existing infrastructure.[60] Nonetheless, in the wake of the 1973 oil embargo, interest in ethanol grew.[61] Over the years, ethanol supporters have offered various rationales for government policies favoring ethanol: energy independence, smog reduction, and environmental sustainability.[62] None of these rationales, however, has proven to be a strong justification for corn ethanol.[63]

Starches and sugars, including those found in corn grain, can be readily converted into ethanol.[64] Ethanol can come from other plant sources as well, including cellulose—an abundant but complex substance found in plant leaves and stalks—but only after intense and costly processing.[65] Corn ethanol in

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[56] *See, e.g.*, Carl Hulse & Michael Janofsky, *Long at Work, Congress Is Set on Energy Bill: Large Subsidies Due Oil and Gas Business*, N.Y. TIMES, July 27, 2005, at A1; Maria Newman, *Bush Signs Sweeping Energy Bill*, N.Y. TIMES, Aug. 8, 2005, http://www.nytimes.com/2005/08/08/politics/08cnd-bush.html (reporting remarks of Senator Pete V. Domenici); David E. Sanger, *President Tours Plant Making Alternative Fuel*, N.Y. TIMES, May 17, 2005, at A15.

[57] Dennis Keeney, *Ethanol USA*, 43 ENVTL. SCI. & TECH. 8, 8–9 (2009).

[58] *Id.* at 9.

[59] This fact was well-established by the mid-1980s. MICHAEL J. GRAETZ, THE END OF ENERGY: THE UNMAKING OF AMERICA'S ENVIRONMENT, SECURITY, AND INDEPENDENCE 130 (2011) (citing a 1986 U.S. Department of Agriculture (USDA) report); *see also* James Bovard, *Archer Daniels Midland: A Case Study in Corporate Welfare*, CATO INSTITUTE 7 (Sept. 26,1995), http://object.cato.org/sites/cato.org/files/pubs/pdf/pa241.pdf (citing 1980 column by Jane Bryant Quinn, who cited an Environmental Protection Agency (EPA) finding of reduced fuel economy with gasohol).

[60] *See* Robert K. Niven, *Ethanol in Gasoline: Environmental Impacts and Sustainability Review Article*, 9 RENEWABLE & SUSTAINABLE ENERGY REVS. 535, 542 (2005); Robert F. Service, *Battle for the Barrel*, 339 SCIENCE 1374, 1376 (2013).

[61] Melissa Powers, *King Corn: Will the Renewable Fuel Standard Eventually End Corn Ethanol's Reign?*, 11 VT. J. ENVTL. L. 667, 679 (2010).

[62] Powers, *supra* note 61, at 679–82; Bovard, *supra* note 59, at 6.

[63] *See, e.g.*, Editorial, *The Ethanol Party*, WALL ST. J., May 26, 2005, at A12; Bovard, *supra* note 59, at 11–15.

[64] *See* WEISS & BONVILLIAN, *supra* note 15, at 99–102.

[65] Service, *supra* note 60, at 1375.

particular has received strong federal and state backing since the 1970s. Policies favoring corn ethanol include direct subsidies, tax exemptions and credits, grants, loans, protective tariffs, and renewable fuel mandates.[66] Perhaps the most significant of these measures have been the renewable fuel standards (RFS) contained in the 2005 and 2007 energy bills. The 2005 law mandated that annual gasoline production contain at least 7.5 billion gallons of renewable fuels by 2012,[67] and the 2007 statute increased that mandate to 36 billion gallons by 2022.[68] Congress anticipated that the 2005 renewable fuels standard would be satisfied primarily by corn ethanol.[69] The 2007 statute, however, requires specific increases in advanced biofuels—a category that excludes corn ethanol—starting in 2016.[70] An excise tax credit ranging between forty and sixty cents per gallon has also provided substantial support for corn ethanol since 1978.[71]

Government support for ethanol has stimulated rapid growth in the ethanol industry but also has raised food prices and contributed to increased air and water pollution.[72] The use of corn to produce fuel directly displaces food production, driving up corn and livestock prices.[73] In addition, corn cultivation demands relatively large amounts of water, fertilizer, and land, resulting in detrimental effects on water quality and supply, land use, soils,

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[66] GRAETZ, *supra* note 59, at 129; Keeney, *supra* note 57, at 8–9; Bovard, *supra* note 59, at 7; Powers, *supra* note 61, at 679–82.

[67] Energy Policy Act of 2005, Pub. L. No. 109–58, § 1501, 119 Stat. 1067, 1069; CONG. RESEARCH SERV., REPORT RL33302, ENERGY POLICY ACT OF 2005: SUMMARY AND ANALYSIS OF ENACTED PROVISIONS 111 (2006).

[68] Energy Independence and Security Act of 2007, Pub. L. No. 110–140, § 202, 121 Stat. 1521, 1522; CONG. RESEARCH SERV., REPORT RL34294, ENERGY INDEPENDENCE AND SECURITY ACT OF 2007: A SUMMARY OF MAJOR PROVISIONS 4 (2007) [hereinafter ENERGY INDEPENDENCE]. The 2007 renewable fuel standards (RFS) are sometimes referred to as "RFS2." *See* CONG. RESEARCH SERV., REPORT R40155, RENEWABLE FUEL STANDARD (RFS): OVERVIEW AND ISSUES 1 (2013) [hereinafter RENEWABLE FUEL STANDARD].

[69] *See* Powers, *supra* note 61, at 708 (noting that 2005 RFS "placed no limits on corn ethanol production and established pitifully weak standards for advanced biofuels").

[70] ENERGY INDEPENDENCE, *supra* note 68, at 5. EPA may waive certain RFS requirements if there is inadequate domestic supply to meet statutorily mandated amounts or if implementation of the requirements would cause severe economic harm. 42 U.S.C. § 7545(o)(7)(A) (2006).

[71] GRAETZ, *supra* note 59, at 129.

[72] U.S. GOV'T ACCOUNTABILITY OFFICE, GAO-09-446, BIOFUELS: POTENTIAL EFFECTS AND CHALLENGES OF REQUIRED INCREASES IN PRODUCTION AND USE 43–44, 51–79 (2009).

[73] Giovanni Sorda et al., *An Overview of Biofuel Policies Across the World*, 38 ENERGY POL'Y 6977, 6977 (2010). Large-scale cellulosic biofuel production can also stress water supplies and displace food crops, though these concerns can be ameliorated by using agricultural or forestry residues and by growing feedstock crops outside prime croplands. COMM. ON AM.'S ENERGY FUTURE, NAT'L ACAD. OF SCIS., AMERICA'S ENERGY FUTURE: TECHNOLOGY AND TRANSFORMATION 89–90 (2009); DEUTCH, *supra* note 44, at 85–86.

and biodiversity.[74] The process of converting corn to ethanol demands additional water, and ethanol's corrosive effect on tanks and pipes heightens groundwater contamination risks.[75]

While there has been much hue and cry regarding corn ethanol's negative consequences, few of these effects come as a surprise. Designed to benefit corn growers, policies promoting ethanol have had their intended effect of driving up corn prices.[76] Ethanol costs taxpayers and consumers billions of dollars per year in subsidies, higher food prices, and higher gasoline bills—a fact that was well anticipated.[77] A 1986 U.S. Department of Agriculture (USDA) study, for example, estimated that each additional dollar of farm income generated by ethanol subsidies would cost taxpayers and consumers four dollars.[78]

Ethanol's environmental consequences were foreseeable as well. From the outset, the net energy value of ethanol was dubious. Life cycle analyses dating back to 1980 suggest that corn ethanol consumes as much or even more energy in its manufacture than is released in its combustion.[79] Subsequent studies have yielded somewhat varying results, depending on underlying data and assumptions regarding corn production, ethanol conversion, and the energy credits allocated for products produced jointly with ethanol.[80] But in no case has there ever been a clear-cut net energy justification for corn ethanol. Simi-

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[74] Keeney, *supra* note 57, at 10; Niven, *supra* note 60, at 546; Tad W. Patzek et al., *Ethanol from Corn: Clean Renewable Fuel for the Future, or Drain on Our Resources and Pockets?*, 7 ENV'T DEV. & SUSTAINABILITY 319, 325 (2005) (noting high nitrogen demand and high soil erosion rates associated with corn cultivation); Service, *supra* note 60, at 1375; *see also* WEISS & BONVILLIAN, *supra* note 15, at 100.

[75] Niven, *supra* note 60, at 542–43; Patzek et al., *supra* note 74, at 325.

[76] GRAETZ, *supra* note 59, at 130; Bill Chalmeides, *Congress's Affair With Ethanol: Love Gone Wrong?*, NATIONAL GEOGRAPHIC (Mar. 28, 2013), http://energyblog.nationalgeographic.com/2013/03/28/ethanol-love-gone-wrong. Before passage of the 2005 renewable fuels mandate, the American Petroleum Institute predicted (correctly as it turns out) higher food costs and little benefit in terms of decreased fossil fuel use. Dan Morgan, *Senate Panel Votes to Boost Ethanol Mandate*, WASH. POST, May 26, 2005, at A8.

[77] *See, e.g.*, *The Ethanol Party*, *supra* note 63.

[78] Bovard, *supra* note 59, at 6 (citing OFFICE OF ENERGY, U.S. DEPT. AGRIC., REPORT NO. 562, FUEL ETHANOL AND AGRICULTURE: AN ECONOMIC ASSESSMENT iv-v (1986)).

[79] DEUTCH, *supra* note 44, at 80–82 (describing 1980 Department of Energy (DOE) Energy Research Advisory Board report concluding that more energy is required to produce ethanol than is contained in it); Niven, *supra* note 60, at 545 (summarizing studies from 1978 to 2002 that analyzed net energy value of ethanol); Patzek et al., *supra* note 74, at 324; David Pimentel et al., *Solar Energy Production Systems*, *in* FOOD, ENERGY, AND SOCIETY 208–09 (David Pimentel & Marcia Pimentel eds., 1996).

[80] WEISS & BONVILLIAN, *supra* note 15, at 99–100; H. Shapouri et al., *The Energy Balance of Corn Ethanol Revisited*, 46 TRANSACTIONS ASAE 959, 960 (2003). Relying on optimistic assumptions, Shapouri et al. ultimately concluded that corn ethanol produces a 34 percent net energy gain. *Id.* at 967. *But cf.* Patzek et al., *supra* note 74, at 323–25 (critiquing USDA report of net energy gain from ethanol).

larly, it is doubtful whether the substitution of corn ethanol for gasoline actually reduces greenhouse gas (GHG) emissions. Studies generally find a net increase in GHG emissions from corn ethanol use, particularly if the conversion of nonagricultural lands to agricultural use as a result of increased corn cultivation is taken into account.[81]

The claim that ethanol reduces conventional air pollution has long been suspect as well. Burning gasoline mixed with ethanol reduces some pollutant emissions but increases others.[82] In 1978, the Environmental Protection Agency (EPA) noted the detrimental effects on air quality from use of ethanol as a fuel.[83] Such effects prompted the 1977 Clean Air Act Amendments to ban the use of oxygenate products, including ethanol, in gasoline.[84] Though similar concerns arose during the 2005 energy bill debate,[85] ethanol advocates successfully framed the fuel as an option that would immediately reduce dependence on foreign oil and that—assuming the successful development of cellulosic ethanol—would one day provide environmental benefits.[86]

Why has the federal government so strongly and consistently supported corn ethanol, notwithstanding one critic's characterization of it as "the single most misguided agricultural program in modern American history?"[87] Similarly, one might ask why Congress enacted the 2005 renewable fuel standard—a

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[81] U.S. GOV'T ACCOUNTABILITY OFFICE, GAO-09-446, BIOFUELS: POTENTIAL EFFECTS AND CHALLENGES OF REQUIRED INCREASES IN PRODUCTION AND USE 80 (2009); Keeney, *supra* note 57, at 10. One 2004 lifecycle analysis found that the use of corn ethanol increased greenhouse gas (GHG) emissions over conventional fossil fuel use by approximately 30 percent. Tad W. Patzek, *Thermodynamics of the Corn-Ethanol Biofuel Cycle*, 23 CRITICAL REVS. PLANT SCIS. 519, 549–50 (2004).

[82] Niven, *supra* note 60, at 537–41; Pimentel, *supra* note 79, at 267; Patzek et al., *supra* note 75, at 325.

[83] Larry Kramer, *EPA Will Allow Continued Sale of Fuel 'Gasohol'*, WASH. POST, Dec. 16, 1978, at A6.

[84] Before enactment of the 1977 Clean Air Act Amendments, the Senate Committee on Environment and Public Works heard testimony on the negative air effects of the fuel additive MMT, an organomanganese compound. S. REP. NO. 95-127, at 90 (1977). MMT "impair[ed] the performance of emission control systems and increase[ed] hydrocarbon emissions in test vehicles." *Id.*; *see* 123 CONG. REC. 18,034 (June 8, 1977) (statement of Sen. Edmund Muskie) (noting Ford Motor Company testimony that MMT "appeared to be damaging their catalysts" and "that the addition of MMT to fuel will cause a significant increase in hydrocarbon emissions"); *see also* David P. Currie, *The Mobile-Source Provisions of the Clean Air Act*, 46 U. CHI. L. REV. 811, 894–96 (1979) (discussing the Senate Committee's fears stemming from "the dangers of MMT and of potential new additives under the existing control provisions" and the resulting ban, as well as EPA issuance of waiver with respect to ethanol).

[85] *See* 151 CONG. REC. S6609-10 (daily ed. June 15, 2005) (statement of Sen. Feinstein); 151 CONG. REC. H2186-87 (daily ed. Apr. 20, 2005) (letter from Rep. Eshoo and other California congresspersons); *see also* SHIRLEY NEFF, REVIEW OF THE ENERGY POLICY ACT OF 2005 2 (2005).

[86] *See* 151 CONG. REC. S6708 (daily ed. June 16, 2005) (statement of Sen. Salazar).

[87] Robert Bryce, *The Corn Ethanol Juggernaut*, YALE ENV'T 360 (Sept. 15, 2008), *available at* http://e360.yale.edu/feature/the_corn_ethanol_juggernaut/2063.

mandate that one U.S. senator described as "odious," "rotten," and "indefensible on the merits"—despite well-established doubts surrounding ethanol.[88] The simple answer to each question is politics. The agricultural industry, led by Archer Daniels Midland (ADM), has aggressively and successfully lobbied for federal support of corn ethanol.[89] ADM's efforts date back to the 1970s, when it sought to create new markets for its corn products by promoting ethanol as a transportation fuel.[90] Since that time, Corn Belt politicians have used their power to direct federal benefits to their home states through ethanol support programs. Concurrently, presidential candidates, acknowledging the pivotal role of Iowa in the nomination process, have consistently pledged support for ethanol.[91] In short, "money, not science, has driven ethanol fuel policy."[92]

Ethanol policy is a prime example of the dangers of political influence in sponsoring energy innovation. Picking energy winners is problematic when politically powerful lobbies warp energy policies and decisions in ways that make little economic or environmental sense. Unfortunately, this problem has no easy solutions. But greater transparency in policymaking, can, at a minimum, expose industry influence to external criticism. In addition, the use of expert panels can insulate grantmaking and other forms of government support from direct political influence.

Finally, the history of ethanol policies demonstrates that life cycle analyses can provide useful information to policymakers striving to develop sound energy policies. Decisionmaking processes must take into account the results of these analyses, of course. The environmental and economic effects of pro-ethanol policies have been fairly well understood since those policies were initiated. Such effects were largely ignored in the face of political pressures. Congress's 2007 revisions to the RFS to specifically promote cellulosic ethanol suggest, however, that it is possible for policymakers to consider information generated by technology assessments and not merely to succumb to pure politics.[93]

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[88] 151 CONG. REC. S9267-68 (daily ed. July 28, 2005) (statement of Sen. Schumer). The mandate was not an obscure provision that Congress overlooked, but rather a central part of the legislative debate. John J. Fialka, *White House Expresses Concern Over Cost of Senate Energy Bill*, WALL ST. J., June 15, 2005, at A4.

[89] GRAETZ, *supra* note 59, at 127–31; Bovard, *supra* note 59; Keeney, *supra* note 57, at 9.

[90] Keeney, *supra* note 57, at 9.

[91] *See* GRAETZ, *supra* note 59, at 131; Bryce, *supra* note 87.

[92] Keeney, *supra* note 57, at 9.

[93] Cellulosic ethanol supporters touted the fuel source's potential to exploit waste materials and to have a lesser impact on food production. *See* NAT'L ECON. COUNCIL, ADVANCED ENERGY INITIATIVE 5–6 (2006), *available at* http://georgewbush-whitehouse.archives.gov/stateoftheunion/2006/energy/energy_booklet.pdf; President George W. Bush, Energy Policy & America's Dependence

B. Hydraulic Fracturing

Whereas corn ethanol represents a long mature technology, hydraulic fracturing appears at first glance to be an energy technology of more recent vintage. Perhaps no technology has transformed the energy sector in the United States more dramatically in recent years than hydraulic fracturing.[94] Deployed in conjunction with horizontal drilling techniques, hydraulic fracturing has enabled oil and gas exploration to occur in new locations, stimulated record levels of oil and gas production, driven down energy costs, and transformed rural economies.[95] The rapid spread of hydraulic fracturing also has been accompanied by health and environmental concerns regarding surface and groundwater contamination, air and land pollution, and seismic disturbances. Given its sudden prominence, hydraulic fracturing would seem to be a prime example of an emerging technology that demands new forms of oversight. The technology of hydraulic fracturing, however, is hardly new. Current hydraulic fracturing techniques combine longstanding practices with gradual technological advances. Moreover, most of the technology's negative effects were not only foreseeable but also somewhat familiar to those conversant in oil and gas drilling activities.

Hydraulic fracturing involves the injection of fluids into a well at high pressure in order to encourage oil or gas to flow into the well.[96] Oil and gas operators have used this basic technique for over sixty years.[97] Slickwater fracturing, the specific type of hydraulic fracturing responsible for the current boom, does incorporate more recent technological innovations. Unlike earlier techniques, which predominantly employed viscous gels,[98] slickwater fracturing combines large volumes of water and limited quantities of gels, sand, or other

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on Oil: Address to the Renewable Fuels Association (Apr. 25, 2006), *available at* http://www.presidentialrhetoric.com/speeches/04.25.06.html.

[94] Produced via hydraulic fracturing techniques, shale gas accounted for almost none of U.S. natural gas production as recently as a decade ago, but now accounts for one-third of such production, and is eventually projected to account for approximately half. *See* ENERGY INFO. ADMIN., WHAT IS SHALE GAS AND WHY IS IT IMPORTANT?, *available at* http://www.eia.gov/energy_in_brief/article/about_shale_gas.cfm (last updated Dec. 5, 2012).

[95] THE WHITE HOUSE, THE BLUEPRINT FOR A SECURE ENERGY FUTURE: PROGRESS REPORT 2 (2012) (noting that U.S. natural gas production is at record levels, and domestic oil production is at its highest level since 2003); *America's Bounty: Gas Works*, ECONOMIST, July 14, 2012, http://www.economist.com/node/21558459.

[96] *See* Hannah Wiseman, *Fracturing Regulation Applied*, 22 DUKE ENVTL. L. & POL'Y F. 361, 361 (2012).

[97] Hannah J. Wiseman, *Risk and Response in Fracturing Policy*, 84 U. COLO. L. REV. 729, 734 n.14 (2013).

[98] Wang & Krupnick, *supra* note 20, at 19–20.

friction-reducing agents.[99] Importantly, the technique is particularly effective in releasing hydrocarbons from shale.[100] The pairing of slickwater fracturing with advanced horizontal drilling techniques has made shale gas production commercially viable and enabled the recovery of previously inaccessible oil deposits.[101]

A closer examination of the history behind these developments offers important lessons for energy technology innovation. George Mitchell, the so-called father of the fracking boom, is often credited with developing slickwater fracturing techniques through years of stubborn persistence, experimentation, and investment under his namesake company, Mitchell Energy.[102] While these efforts indeed played a critical role, Mitchell Energy also benefited from favorable government policies, including incentive pricing, tax credits, and research and development programs for unconventional natural gas production.[103] Support from the Department of Energy (DOE) proved to be of particular value, although that value was not immediately appreciated.[104] For examexample, DOE partnered with industry to introduce horizontal drilling techniques and large-scale hydraulic fracturing to gas shales, and to develop microseismic mapping techniques that optimize well stimulation.[105] Slickwater fracturing has capitalized on insights from these different lines of inquiry, demonstrating the value of research efforts with future applications that may be uncertain, as well as the value of sustained public investments in energy technology demonstration projects and in technology diffusion.[106]

Slickwater fracturing's emergence from unexpected synergies between different innovations suggests a further lesson: Technology assessment should be an ongoing process rather than a discrete event. Technologies are

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[99] Wiseman, *supra* note 96, at 362 & n.8.

[100] *Id.* at 362.

[101] SEC'Y OF ENERGY ADVISORY BD., U.S. DEPT. OF ENERGY, SHALE GAS PRODUCTION SUBCOMMITTEE 90-DAY REPORT 8 (2011).

[102] *See, e.g.*, Tom Fowler, *Exec Mitchell Laid Groundwork for Shale Gas Surge*, HOUS. CHRON. (Nov. 15, 2009), http://www.chron.com/business/energy/article/Exec-Mitchell-laid-groundwork-for-shale-gas-surge-1742206.php; Christopher Helman, *Father of the Fracking Boom Dies - George Mitchell Urged Greater Regulation of Drilling*, FORBES (July 27, 2013, 6:31 PM), http://www.forbes.com/sites/christopherhelman/2013/07/27/father-of-the-fracking-boom-dies-george-mitchell-urged-greater-regulation-of-drilling.

[103] Wang & Krupnick, *supra* note 20, at 6–7, 10–14, 25–26 (2013); JASON BURWEN & JANE FLEGAL, AM. ENERGY INNOVATION COUNCIL, UNCONVENTIONAL GAS EXPLORATION & PRODUCTION 3–7 (2013); Michael Shellenberger & Ted Nordhaus, op-ed, *A Boom in Shale Gas? Credit the Feds*, WASH. POST (Dec. 16, 2011), http://www.washingtonpost.com/opinions/a-boom-in-shale-gas-credit-the-feds/2011/12/07/gIQAecFIzO_print.html.

[104] *See* Shellenberger & Nordhaus, *supra* note 103; Wang & Krupnick, *supra* note 20, at 10–14.

[105] Wang & Krupnick, *supra* note 20, at 10–14.

[106] BURWEN & FLEGAL, *supra* note 103, at 7–8; Shellenberger & Nordhaus, *supra* note 103.

dynamic, combining with complementary innovations and adapting to different contexts. To account for changing conditions and new information, society should continually assess emerging technologies and monitor them for potential hazards. Indeed, the emerging technologies warranting careful attention should include not only new technical breakthroughs but also technologies that are emerging as commercially important.

The history of slickwater fracturing even offers grounds for cautious optimism regarding our capacity to manage emerging technology risks. On the one hand, the development of slickwater fracturing has had dramatic and widespread consequences of which few experts warned. On the other hand, a review of the environmental issues associated with the technique reveals few truly novel concerns. As a leading legal commentator has noted, "[m]any of the core risks of fracturing appear to arise not from the technology itself but from the enhanced oil and gas *drilling* activity that it inspires in certain areas—activity that has long occurred but has changed in scale."[107] These risks include the migration of methane from improperly cased wells and well blowouts, water and soil contamination from drilling fluids or drilling wastes, and air pollution from drilling operations and leaking pipelines.[108] In some instances, slickwater fracturing has expanded the scope of hazards because it requires large quantities of water, uses new chemicals, and deploys horizontal and sometimes deeper wells.[109] The resultant hazards—chemical spills, reduced water availability, contamination from wastewater—are largely familiar from conventional oil and gas drilling activity.[110] Even the increased seismic activity sometimes traced to the fracturing process or wastewater disposal reflects long-known hazards arising from the injection of fluids into underground formations.[111]

Such hazards merit careful oversight and further investigation.[112] In contrast to some of the hazards raised by truly emergent technologies like synthetic biology, however, most slickwater fracturing hazards can be addressed through conventional and well-understood means, including better drilling

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[107] Wiseman, *supra* note 97, at 778.

[108] *Id.* at 778–808.

[109] *Id.* at 757–58.

[110] *See id.*

[111] *See* William L. Ellsworth, *Injection-Induced Earthquakes*, 341 SCIENCE 142, 142 (2013).

[112] EPA is in the process of studying more precisely the impacts of slickwater fracturing on drinking water resources, for example. Congress did not order EPA to conduct the study until 2009, however, and a draft report is not due to be released until 2014. ENVTL. PROT. AGENCY, PLAN TO STUDY THE POTENTIAL IMPACTS OF HYDRAULIC FRACTURING ON DRINKING WATER RESOURCES 1, 7 (2011).

practices and proper wastewater disposal techniques.[113] For instance, requiring adequate well casing and blowout preventers can reduce the risk of groundwater contamination; mandating wastewater treatment or recycling can address concerns regarding soil and surface water contamination; and prescribing capture of methane emissions can reduce climate change impacts.[114] Overall, the cost of implementing adequate environmental protections at an average shale gas well would increase drilling costs by a modest 7 percent, according to an International Energy Agency estimate.[115]

Political resistance, not ignorance of potential adverse effects, has been the primary obstacle to mandating such protections. Hydraulic fracturing has been widely embraced by government and industry, as it produces fossil fuels already in widespread use and complements existing energy systems. Whereas state regulation of this activity varies widely and, in many instances, is just starting to address some of the hazards, federal regulation is minimal.[116] Perhaps the best-known instance of federal deregulation is a 2005 energy bill exemption of fractured wells from Safe Drinking Water Act oversight.[117] Sometimes referred to as the Halliburton loophole, this exemption was recommended by Vice President Dick Cheney's Energy Task Force to spur energy production and reflected industry recognition of the growing importance of hydraulic fracturing

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[113] *See* INT'L ENERGY AGENCY, GOLDEN RULES FOR A GOLDEN AGE OF GAS 9, 13–14 (2012) [hereinafter GOLDEN RULES] (proposing "Golden Rules" that employ existing techniques to address environmental and social impacts of unconventional gas extraction); Joe Nocera, *About My Support for Natural Gas*, N.Y. TIMES, Apr. 15, 2011, at A21; Wiseman, *supra* note 97, at 809–11 (recommending that regulatory authorities revise policies and regulations to account for risks and generate more information). George Mitchell advocated that operators be subject to DOE regulation and required to follow best drilling practices. *See* Christopher Helman, *Billionaire Father of Fracking Says Government Must Step Up Regulation*, FORBES (July 19, 2012, 8:29 AM), http://www.forbes.com/sites/christopherhelman/2012/07/19/billionaire-father-of-fracking-says-government-must-step-up-regulation.

[114] Wiseman, *supra* note 97, at 770–74, 779–87; *see also* GOLDEN RULES, *supra* note 113, at 13–14.

[115] GOLDEN RULES, *supra* note 113, at 10.

[116] *See* David B. Spence, *Federalism, Regulatory Lags, and the Political Economy of Energy Production*, 161 U. PA. L. REV. 431, 447–57 (2013) (noting absence of "comprehensive federal licensing regime for onshore oil and gas development," describing regulatory exemptions from federal environmental laws for such development, and comparing state regulatory regimes applicable to hydraulic fracturing in three states); *see also* Jody Freeman, op-ed, *The Wise Way to Regulate Gas Drilling*, N.Y. TIMES, July 6, 2012, at A23 (criticizing "patchwork" of state regulatory approaches as bad for the environment and for industry); Wiseman, *supra* note 96, at 367 (noting variety of state approaches). In September 2013, California adopted legislation that established a permitting process for hydraulic fracturing and other well-stimulation operations in the state. California S.B. 4, 2013-2014 Reg. Sess. (Cal. 2013).

[117] Energy Policy Act of 2005, Pub. L. No. 109-58, § 322, 119 Stat. 594, 694 (amending 42 U.S.C. § 300h(d) to exclude from EPA's existing regulatory authority the underground injection of fluids in hydraulic fracturing operations, with the exception of diesel fuel injection).

techniques.[118] The task force focused narrowly on the use of hydraulic fracturing to generate coal bed methane, not its use in shales. Nonetheless, its analysis foreshadowed some of the environmental concerns later raised by the hydraulic fracturing boom, including proper wastewater disposal.[119] Indeed, reports contemporaneous with the debate over the 2005 energy bill identified various environmental concerns, including drinking water contamination and increased water demand.[120] Such concerns were the subject of extensive congressional debate.[121] While the extent of hydraulic fracturing's negative consequences was uncertain and remains context-dependent, there was a general recognition that hydraulic fracturing would have adverse environmental effects.[122]

In sum, slickwater fracturing largely has not involved "unknown unknowns," which pose perhaps the most difficult challenge for technology

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[118] Dianne Rahm, *Regulating Hydraulic Fracturing in Shale Gas Plays: The Case of Texas*, 39 ENERGY POL'Y 2974, 2977 (2011); *see also* 151 CONG. REC. S5533 (daily ed. May 19, 2005) (statement of Sen. Jeffords) (citing industry projections that 90 percent of U.S. oil and gas wells would be accessed through hydraulic fracturing). Halliburton pioneered new horizontal drilling techniques and was an early participant in the fracking boom. *See* John J. Fialka, *Second Look: Wildcat Producer Sparks Oil Boom on Montana Plains*, WALL ST. J., Apr. 5, 2006, at A1; Tom Hamburger & Alan C. Miller, *Halliburton's Interests Assisted by White House*, L.A. TIMES, Oct. 14, 2004, at A1; Judy Pasternak, *Bush's Energy Plan Bares Industry Clout*, L.A. TIMES, Aug. 26, 2001, at A1.

[119] NAT'L ENERGY POLICY DEV. GRP., NATIONAL ENERGY POLICY: RELIABLE, AFFORDABLE, AND ENVIRONMENTALLY SOUND ENERGY FOR AMERICA'S FUTURE 5-5 (2001). It has been known for some time that hydraulic fracturing to produce coal bed methane can contaminate drinking water supplies. *See* Legal Envtl. Assistance Found., Inc. v. U.S. Envtl. Prot. Agency, 118 F.3d 1467, 1471 (11th Cir. 1997) (citing 1990 EPA study).

[120] *See* Hannah Wiseman, *Untested Waters: The Rise of Hydraulic Fracturing in Oil and Gas Production and the Need to Revisit Regulation*, 20 FORDHAM ENVTL. L. REV. 115, 128–37 (2009) (discussing reports). A 2004 EPA report did conclude that hydraulic fracturing operations to produce coal bed methane, which occur at more shallow depths than shale fracturing operations, "pose[] little or no threat" to underground sources of drinking water. ENVTL. PROT. AGENCY, EVALUATION OF IMPACTS TO UNDERGROUND SOURCES OF DRINKING WATER BY HYDRAULIC FRACTURING OF COALBED METHANE RESERVOIRS STUDY, ES-1 (2004). Many have questioned the scope and integrity of that report, however. *See, e.g.*, Wiseman, *supra* at 128–36 (discussing limitations of EPA study); Editorial, *The Halliburton Loophole*, N.Y. TIMES, Nov. 3, 2009, at A28 (noting that EPA study "was dismissed by experts as superficial and politically motivated"); Letter from Weston Wilson, EPA Employee, to Sen. Wayne Allard et al. (Oct. 8, 2004), *available at* http://latimes.image2.trb.com/lanews/media/acrobat/2004-10/14647025.pdf (letter from EPA whistleblower).

[121] *See* Tom Hamburger & Alan C. Miller, *Investigation of Drilling Regulations Is Urged*, L.A. TIMES, Oct. 15, 2004, at A15; *see also* 151 CONG. REC. S5533–37 (daily ed. May 19, 2005) (statement of Sen. Jeffords) (discussing potential negative effects on drinking water and introducing a bill to regulate hydraulic fracturing under the Safe Drinking Water Act); 151 CONG. REC. S9336–37 (daily ed. July 29, 2005) (statement of Sen. Feingold); 151 CONG. REC. S9346–47, S9349 (daily ed. July 29, 2005) (statement of Sen. Jeffords); 151 CONG. REC. S9351 (daily ed. July 29, 2005) (statement of Sen. Lieberman).

[122] *See* Wiseman, *supra* note 120, at 140–41.

prognosticators. Slickwater fracturing's adverse consequences were in fact foreseeable, even if they were not actually foreseen. The failure to plan for and address these consequences resulted, in part, from a failure to predict the technique's rapid adoption. At the turn of the century, neither the government nor industry forecasted the energy boom that would follow.[123] But even after key players recognized the revolutionary changes underway, oversight has been slow to arrive. In general, there has been little political will to rein in an activity that has generated revenue to states and local communities and provided a welcome lift to the entire U.S. economy.

Federal policy on hydraulic fracturing thus shares important commonalities with policy on corn ethanol. In each instance, politically powerful players have secured favorable legal treatment that enabled widespread use of the technology. Government has not merely picked technology winners; it has awarded spoils to parties that arguably need them least. In the process, legislators and regulators have made conscious decisions to disregard identifiable environmental hazards and other adverse consequences.

C. Nuclear Energy

The final case study in this Part considers nuclear energy, which has a history of particularly heavy government involvement. Once touted as a technology that might satisfy virtually all our energy needs, nuclear power now generates approximately 20 percent of electricity in the United States (and 13 percent worldwide).[124] The technology has been deployed for five decades, and researchers continue to work on improving current technology and developing next-stage advances, such as nuclear fusion. Though nuclear energy generates no carbon emissions, it remains controversial. Moreover, its future is uncertain thanks to high capital costs, safety and waste management issues, and proliferation risks.[125] America's experience with nuclear energy nonetheless offers useful insights for emerging energy technologies with respect to establishing new technologies, identifying risks, incorporating public values, and building public trust.

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[123] *See, e.g.*, ENERGY INFO. ADMIN., ANNUAL ENERGY OUTLOOK 2000, at 74–80 (1999) (relating projections regarding oil and natural gas production and reserves).

[124] GRAETZ, *supra* note 59, at 77; Oliver Morton, *The Dream That Failed*, ECONOMIST, May 10, 2012, http://www.economist.com/node/21549098.

[125] DEUTCH, *supra* note 44, at 98; *see also* JOHN M. DEUTCH ET AL., UPDATE OF THE MIT 2003 FUTURE OF NUCLEAR POWER (2009) (discussing challenges facing nuclear power).

Like many other energy technologies, nuclear power followed a long path to development and commercialization. As World War II ended, scientists, politicians, and others recognized the potential peaceful uses of atomic energy. They envisioned not only large power plants to supply energy to millions of households, but also small-scale plants to power individual homes and even portable atomic generators to provide personalized climate control.[126] At that point, however, civilian applications were still many years off. In fact, the Atomic Energy Commission (AEC) predicted in 1947—accurately, as it turned out—that a nuclear power demonstration project was eight to ten years away and that significant deployment of nuclear power would not occur for two decades.[127]

Because of the national security, health, and financial risks associated with nuclear energy, the government has always participated actively in the field.[128] Congress put the AEC in charge of both military and civilian uses of atomic energy, with its military functions taking priority.[129] As for civilian applications, the agency held dual and conflicting responsibilities: It was to promote peaceful uses of atomic energy and also to regulate accompanying health and safety risks.[130] The AEC ultimately emphasized development over regulation as it engaged in research, prototyping, and demonstration projects in collaboration with the private sector.[131] The agency was reluctant to place substantial obstacles before a technology in which it had heavily invested and thus imposed only those safety constraints "consistent with the commercial viability of the nuclear power reactor."[132]

Elected officials and regulators were nonetheless cognizant of safety concerns from the start, particularly the potential for nuclear meltdowns and the release of radioactive materials.[133] Radioactive fallout from nuclear bomb

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[126] *See* MAZUZAN & WALKER, *supra* note 37, at 2.

[127] GRAETZ, *supra* note 59, at 67.

[128] Gallagher et al., *supra* note 15, at 203.

[129] Atomic Energy Act of 1946, ch 724 §§ 2, 6, 60 Stat. 756 (1946) (establishing the Atomic Energy Commission); MAZUZAN & WALKER, *supra* note 37, at 4. *See generally* ALICE L. BUCK, U.S. DEP'T OF ENERGY, A HISTORY OF THE ATOMIC ENERGY COMMISSION 1–3 (1983).

[130] Atomic Energy Act of 1954, ch. 1073, 68 Stat. 919 (1954) (codified at 42 U.S.C. §§ 2011-2297h-12). With the passage of this Act, the Atomic Energy Commission (AEC) began to transfer the new technology to the private sector. Diane Carter Maleson, *The Historical Roots of the Legal System's Response to Nuclear Power*, 55 S. CAL. L. REV. 597, 601 (1982); John Gorham Palfrey, *Energy and the Environment: The Special Case of Nuclear Power*, 74 COLUM. L. REV. 1375, 1391–92 (1974).

[131] *See* MAZUZAN & WALKER, *supra* note 37, at 418–19; BUCK, *supra* note 129, at 3 (describing the AEC's cooperation with industry); Maleson, *supra* note 130, at 603.

[132] ELIZABETH S. ROLPH, NUCLEAR POWER AND THE PUBLIC SAFETY: A STUDY IN REGULATION 77 (1979).

[133] *See id.* at 68–69.

tests beginning in the mid-1950s prompted public concern regarding radiation exposure in general.[134] Although there were large gaps in knowledge regarding radiation's effects on people and the environment, a 1956 National Academy of Sciences (NAS) report warned that the proliferation of atomic power plants and other nonmilitary sources of radiation eventually could have serious health effects for the general public.[135] Fears of crippling liability threatened private investment in nuclear energy, prompting the enactment of the Price-Anderson Act in 1957.[136] Significant features of the Act include a requirement that operators obtain primary insurance coverage from a private insurer, the creation of a secondary insurance pool into which all operators would pay retroactively if damages at a facility exceed the primary coverage limit, a federal promise to provide relief should the primary and secondary insurance pools be exhausted, and a liability cap.[137] These provisions not only played a critical role in enabling the commercialization of nuclear power but also promised compensation for harms resulting from the technology.[138]

As the new technology developed, the AEC recognized that building public confidence was essential to nuclear energy's success and thus set about to study and delineate possible hazards.[139] Initially, the agency seemed to succeed in assuring the public. One historical account found "little evidence of public opposition to atomic power for electrical production or uneasiness about its safety" between 1954 and 1962, just as commercialization of the technology began.[140] The agency's tendency to downplay risks and gloss over uncertainties, however, eventually undermined its credibility.[141]

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[134] MAZUZAN & WALKER, *supra* note 37, at 32, 41.

[135] *Id.* at 44–47 (citing NAT'L ACAD. OF SCI'S-NAT'L RESEARCH COUNCIL, THE BIOLOGICAL EFFECTS OF ATOMIC RADIATION: A REPORT TO THE PUBLIC (1956)).

[136] GRAETZ, *supra* note 59, at 67; MAZUZAN & WALKER, *supra* note 37, at 208–12. Although the Act was originally intended to protect the nuclear industry for only ten years, it has been repeatedly authorized, most recently by the 2005 Energy Policy Act. Energy Policy Act of 2005, Pub. L. No. 109-58, § 602, 119 Stat. 779 (2005); *see* David M. Rocchio, *The Price-Anderson Act: Allocation of the Extraordinary Risk of Nuclear Generated Electricity*, 14 B.C. ENVTL. AFF. L. REV. 521, 524 & n.19 (1987).

[137] 42 U.S.C. § 2210.

[138] *See* Taylor Meehan, *Lessons from the Price-Anderson Nuclear Industry Indemnity Act for Future Clean Energy Compensatory Models*, 18 CONN. INS. L.J. 339, 343–44 (2011); Daniel W. Meek, Note, *Nuclear Power and the Price-Anderson Act: Promotion Over Public Protection*, 30 STAN. L. REV. 393, 393–94 (1978).

[139] *See* MAZUZAN & WALKER, *supra* note 37, at 421.

[140] *Id.* at 422 (citing 1956 survey finding that 69 percent of respondents had "no fear" of having a nuclear plant in their community, as opposed to 20 percent who did have such fear).

[141] *See* GRAETZ, *supra* note 59, at 67; MAZUZAN & WALKER, *supra* note 37, at 58, 420–24; Palfrey, *supra* note 130, at 1387.

In the 1960s, as construction of nuclear plants ramped up and concerns over radioactive fallout from atmospheric weapons testing grew, nuclear power became the subject of intense public controversy.[142] Coal interests, fearful of growing competition from the nascent nuclear industry, highlighted safety concerns and stoked the public controversy that continues today.[143] Eventually, growth in the nuclear industry stalled. Orders for new nuclear power plants peaked in the early 1970s, fell precipitously in subsequent years, and ground to a halt after the 1979 accident at Three Mile Island.[144] Growing public unease—shaped by Three Mile Island and subsequent accidents at Chernobyl and Fukushima Daiichi—has contributed as but one of a number of causes of nuclear energy's struggles.[145] Delays and high capital costs, especially in comparison to fossil fuel power plants, plagued many projects.[146] Even today, capital costs remain sufficiently high that nuclear plants cannot be built without subsidy or external support.[147]

The well-documented history of nuclear energy development offers a number of important lessons in managing emerging energy technologies, particularly those involving catastrophic risks and substantial uncertainty.

First, the measured pace of energy technology development, combined with the barriers to energy innovation, allow some time to evaluate risks and to engage the public. Nuclear power took two decades to achieve commercialization, even with strong government backing. This time provided an opportunity to assess risks, and indeed, substantial risk information was available before commercialization. For example, while acknowledging the need for more research, the 1956 NAS report noted that scientists knew more about the hazards of radiation than they knew about hazards from new industrial chemicals and pharmaceuticals.[148] Both government and industry recognized the need to provide safety assurances to the public, and both devoted signifi-

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[142] J. SAMUEL WALKER, CONTAINING THE ATOM: NUCLEAR REGULATION IN A CHANGING ENVIRONMENT, 1963–1971, at 387–414 (1992).

[143] *See id.* at 394.

[144] GRAETZ, *supra* note 59, at 65.

[145] *See, e.g.*, *Nuclear Power in the American Mind*, YALE PROJECT ON CLIMATE CHANGE COMM., http://environment.yale.edu/climate-communication/article/nuclear-power-in-the-american-mind (last visited Feb. 2, 2014) (reporting associations of nuclear power with disaster and danger).

[146] GRAETZ, *supra* note 59, at 65–66.

[147] Morton, *supra* note 124.

[148] MAZUZAN & WALKER, *supra* note 37, at 46.

cant resources to studying the hazards of nuclear power.[149] Nonetheless, regulators ultimately were unprepared to analyze and manage risks associated with full-scale deployment because they failed to anticipate the size and number of facilities that developed.[150]

Second, the history of nuclear energy illustrates the importance of transparency and trust in eliciting public views and obtaining public support. The slow pace of nuclear development and commercialization provided an opportunity for public debate about the technology and its risks.[151] Operating against the backdrop of secrecy that enshrouded nuclear weapons, however, the AEC acted too slowly to open up its analyses and regulatory activities to the public.[152] The AEC's secretive ways and pro-development bias undercut its efforts to convince the public that nuclear power was safe, and the agency's languid response to regulatory concerns exacerbated the problem.[153] Lack of confidence in the agency went hand in hand with lack of confidence in the technology. Ideally, an open public discussion of the merits and risks of nuclear energy would have fostered consideration of whether and how to proceed. In the absence of such a discussion, the public essentially forced a debate through litigation and public protests.[154] Future efforts to establish high-profile, and potentially controversial, energy technologies should adopt a more open and inclusive approach, preferably before key stakeholders have already committed to a particular technology. Furthermore, the AEC's struggle to both promote and regulate nuclear energy offers a warning regarding institutional design. These two functions—promotion and regulation—should remain separate: The EPA or some other regulatory agency should have regulatory jurisdiction over these technologies, while DOE innovation agencies such as ARPA-E should support energy research and development and engage in technology assessment.[155]

Third, the visibility of an energy technology matters in attracting attention and prompting legal and policy responses. A number of factors make nu-

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[149] *See* Palfrey, *supra* note 130, at 1397, 1400–01 (contending that the inherently dangerous nature of nuclear technology gave AEC and industry strong incentives to develop accurate safety information).

[150] *See* ROLPH, *supra* note 132, at 157.

[151] *See, e.g.*, WALKER, *supra* note 142, at 420–21 (discussing contrasting assessments of nuclear power that developed during the 1960s).

[152] *See* Palfrey, *supra* note 130, at 1387, 1397–1400. Indeed, as public concerns increased, the AEC sought unsuccessfully to reduce public participation in the licensing process. *See* ROLPH, *supra* note 132, at 116.

[153] *See* WALKER, *supra* note 142, at 390, 413.

[154] *See* GRAETZ, *supra* note 59, at 72–75.

[155] *See generally* Tomain, *supra* note 28, at 414–27 (discussing existing and proposed energy innovation agencies).

clear energy especially conspicuous and controversial. Nuclear energy is unlike deepwater oil and gas extraction, which proliferated largely out of public view until the Deepwater Horizon accident. Rather, nuclear plants are physically large and costly, and the construction of a nuclear plant provides a focal point for inquiry and opposition.[156] Furthermore, nuclear power is associated with psychologically prominent and dramatic risks.[157] People tend to worry especially about large-scale harms and to focus on the magnitude of these harms, rather than the likelihood of their occurrence.[158] The nuclear industry, moreover, has never succeeded in clearly distinguishing the civilian use of nuclear power from its military applications; indeed, opponents of nuclear power repeatedly sought to link the two.[159] Not all emerging energy technologies share nuclear energy's high public profile, however. Absent a dramatic event that captures the headlines, concerted efforts to focus attention on such technologies may be necessary to prompt public discourse regarding desired energy systems and acceptable risks.

Finally, government support is likely necessary for the establishment of new energy technologies, particularly those that may disrupt existing energy systems. Although the need today for the Price-Anderson Act's various components is debatable,[160] the Act and other forms of government support were critical to establishing nuclear energy. The combination of a new technology, large-magnitude risk and uncertainty, high capital costs, and significant barriers to entry warranted government support in the 1950s, and the Act's liability cap and insurance provisions addressed fears of liability for catastrophic harms.[161]

D. Summing Up

The preceding case studies underscore the gradual and capital-intensive nature of energy technology development. We should not expect immediate

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[156] *Cf.* WALKER, *supra* note 142, at 392–93 (noting that growing public opposition to construction of new nuclear plants reflected objections to specific sites as well as concern over cumulative effects of industry expansion).

[157] *See* DEUTCH, *supra* note 44, at 96–97; *see also* WALKER, *supra* note 142, at 412 (contrasting readily dramatized hazards of nuclear energy with the technology itself, which is complex and difficult to explain).

[158] *See generally* Dale Griffin & Amos Tversky, *The Weighing of Evidence and the Determinants of Confidence*, *in* HEURISTICS AND BIASES: THE PSYCHOLOGY OF INTUITIVE JUDGMENT 230, 230–32 (Thomas Gilovich et al. eds., 2002) (discussing overconfidence bias); Cass R. Sunstein, *Terrorism and Probability Neglect*, 26 J. RISK AND UNCERTAINTY 121, 122–28 (2003).

[159] *See* WALKER, *supra* note 142, at 399.

[160] *See, e.g.*, Rocchio, *supra* note 136, at 524–26.

[161] *See* MAZUZAN & WALKER, *supra* note 37, at 93–97.

technological solutions to our energy challenges. In light of the obstacles new energy technologies face, government must play a significant role not only in research and development but also in demonstration projects and other precursors to commercialization. Such support is especially necessary for establishing disruptive energy technologies.

To some extent, government inevitably engages in picking winners as it makes energy investments. The key to success is doing so in a manner that is reasonably informed and not dominated by political patronage. Society can take advantage of the measured pace of energy innovation to promote informed decisions. Although policymakers may not fully understand the precise hazards of each technology at the outset, hints of such hazards are often present and can prompt further study as a technology moves toward deployment. Political patronage is difficult to avoid, particularly with large sums at stake. But including experts in decisionmaking processes and insulating such processes from direct political control can help. Transparency can also promote decisions that are more publicly justifiable.

These last points suggest the value of periodically conducting broad and open public discussions regarding energy policy. Vice President Dick Cheney's Energy Task Force provides a starting point—though not a model—for considering how these discussions might occur. Widely criticized for holding dozens of nonpublic meetings with industry representatives, the Task Force compiled a sweeping report, which included recommendations that served as the basis for subsequent legislation and executive actions.[162] The process followed by the Task Force left much to be desired, but the group's avowed purpose of "develop[ing] a national energy policy designed to . . . promote dependable, affordable, and environmentally sound production and distribution of energy for the future" was a worthy one.[163] Ideally, such a goal would be pursued through a truly open and deliberative process involving experts, stakeholders, and citizens.[164]

III. EMERGING ENERGY TECHNOLOGIES OF THE FUTURE

This Part turns to three emerging energy technologies—methane hydrates, algal biofuels, and nanosolar—with the objective of applying lessons learned above. These three emerging technologies serve as useful examples because

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[162] *See* Eric Dannenmaier, *Executive Exclusion and the Cloistering of the Cheney Energy Task Force*, 16 N.Y.U. ENVTL. L.J. 329, 330–32 (2008).

[163] NAT'L ENERGY POLICY DEV. GRP., *supra* note 119, at viii (quoting President George W. Bush).

[164] *Cf.* Markku Lehtonen & Florian Kern, *Deliberative Socio-Technical Transitions*, *in* ENERGY FOR THE FUTURE, *supra* note 42, at 103, 110–13.

they vary in their compatibility with existing energy systems and in their potential environmental effects. Methane hydrates—a potentially prodigious source of natural gas that is now economically impossible to extract—would prolong our heavy reliance on fossil fuels. Algal biofuels—a subcategory of advanced biofuels that some envision as environmentally superior to corn ethanol—would compete against corn ethanol and conventional transportation fuels but could be incorporated fairly readily within existing energy systems. Finally, nanosolar—a set of advances in solar energy generation enabled by nanotechnology—could facilitate a transition to renewable energy but also raises new environmental concerns.

A. Methane Hydrates

Methane hydrates are a crystalline form of natural gas found in permafrost and ocean sediments on the continental margins.[165] In these environments, high pressure and low temperatures trap high concentrations of methane within crystalline cages formed by water molecules.[166] The amount of energy trapped in this form may exceed the energy contained in all previous oil and gas discoveries combined.[167] Japan, China, and other countries with limited domestic energy resources have shown particular interest in developing techniques for harvesting gas from methane hydrates located offshore.[168] Extraction has proven difficult and expensive, however, as "the gas is in a solid form and deposits occur in remote and hostile . . . environments."[169] In light of these difficulties, estimates place commercial production at a decade or more away.[170]

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[165] Volker Krey et al., *Gas Hydrates: Entrance to a Methane Age or Climate Threat?*, ENVTL. RESEARCH LETTERS 2 (Sept. 7, 2009), http://iopscience.iop.org/1748-9326/4/3/034007/pdf/1748-9326_4_3_034007.pdf.

[166] Krey et al., *supra* note 165, at 2; *see* Ben Lefebvre, *Fracking Dreams of a New Ice Age*, WALL. ST. J., July 29, 2013, at B1; Carolyn D. Ruppel, *Methane Hydrates and Contemporary Climate Change*, NATURE EDUC. (2011), http://www.nature.com/scitable/knowledge/library/methane-hydrates-and-contemporary-climate-change-24314790.

[167] Lefebvre, *supra* note 166, at B1. Much of this inventory may be technically or economically inaccessible because it is dispersed over large areas. NAT'L RESEARCH COUNCIL, REALIZING THE ENERGY POTENTIAL OF METHANE HYDRATE FOR THE UNITED STATES 33 (2010) [hereinafter NRC, REALIZING THE ENERGY POTENTIAL OF METHANE HYDRATE].

[168] Lefebvre, *supra* note 166, at B1; Krey et al., *supra* note 165, at 4.

[169] NRC, REALIZING THE ENERGY POTENTIAL OF METHANE HYDRATE, *supra* note 167, at 52.

[170] Lefebvre, *supra* note 166, at B1; Carolyn Ruppel, *Methane Hydrates and the Future of Natural Gas*, *Supplementary Paper in* THE FUTURE OF NATURAL GAS 1, 15 (MIT ENERGY INITIATIVE, 2011), *available at* http://mitei.mit.edu/system/files/Supplementary_Paper_SP_2_4_Hydrates.pdf (characterizing methane hydrates as "probably the least likely of [the] unconventional resources to be tapped for natural gas within the next few decades").

Notwithstanding substantial barriers, eventual commercial success is certainly possible. The allure of energy independence gives Japan and other energy-poor nations a strong incentive to pursue methane hydrate recovery. A recent test sponsored by the Japanese government, for example, recovered just over four million cubic feet of gas from methane hydrates.[171] Moreover, because the natural gas that methane hydrates would yield readily fits within existing energy systems, powerful interests would likely embrace the technology if it were successfully developed. Like the shale gas believed to be inaccessible before the current hydraulic fracturing boom, methane hydrates are difficult to extract but simply too valuable to dismiss.

Methane hydrate extraction could trigger the accidental release of large amounts of methane from unstable ocean sediments. Methane is a far more potent GHG than carbon dioxide, and massive methane releases would exacerbate climate change. But experts deem it unlikely that a sudden release would have immediate catastrophic effects because most of the methane that could escape from the ocean floor would either remain in solid form, dissolve into the ocean, or be converted into carbon dioxide.[172] Leaks of methane during the production process arguably pose a greater environmental risk.[173] Although somewhat comparable to the leaks associated with hydraulic fracturing, such hazards are poorly understood and would require greater attention before commercialization.[174]

Perhaps the most significant environmental effects of methane hydrate development would arise from its impact on overall fossil fuel use. The augmentation of methane supplies, particularly in nations where methane is not readily available, would increase fossil fuel dependence and threaten further climate change.[175] Though some envision natural gas as a bridge fuel to a renewable energy future, there is little assurance that this fuel will be relin-

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[171] Lefebvre, *supra* note 166, at B1.

[172] Charles C. Mann, *What If We Never Run Out of Oil?*, ATLANTIC, May 2013, at 48, 62; *see also* Ruppel, *supra* note 166.

[173] *See* NRC, REALIZING THE ENERGY POTENTIAL OF METHANE HYDRATE, *supra* note 167, at 67–72 (discussing geohazards and environmental issues related to methane hydrate production); Mann, *supra* note 172, at 62 (reporting experts' views).

[174] *See* NRC, REALIZING THE ENERGY POTENTIAL OF METHANE HYDRATE, *supra* note 167, at 104–05, 135–36. Methane release might occur not only during extraction of methane hydrates but also in response to warming of the oceans and permafrost regions. Krey et al., *supra* note 165, at 4–5; Ruppel, *supra* note 166. Indeed, the capture and use of methane hydrates released as a result of global warming could help mitigate further warming. Krey et al., *supra* note 165, at 5.

[175] *See generally* Lefebvre, *supra* note 166, at B1; Mann, *supra* note 172, at 51.

quished if it is abundant and remains cheaper than alternative energy sources.[176]

While it may be too early to establish regulatory regimes governing the specific hazards of methane hydrate extraction, the preceding case studies—particularly that of hydraulic fracturing—offer several instructive lessons with immediate application. First, many of the environmental concerns associated with slickwater fracturing stem from expanded drilling activity rather than new technologies per se. Methane hydrate extraction would rely on new technologies, to be sure, and researchers and regulators should be on the lookout for new hazards. But as noted above, the risk of a sudden and catastrophic methane release appears minimal. Attending to familiar hazards, such as leaks during production, will likely be more important and achievable.[177] Present efforts should focus on developing rules and techniques for minimizing these hazards.[178]

Furthermore, assessment of methane hydrate technologies should be ongoing to ensure that policymakers are ready to act when necessary. Research and development efforts on methane hydrates should not occur in a policy vacuum.[179] Decisions to pursue methane hydrates would have important implications for energy policy and climate change. Accordingly, policymakers should seek public input before the technology is developed and should address climate change concerns jointly with the energy security concerns that are driving methane hydrate research.[180] Putting a global price on carbon, for example, would create incentives for governments and other actors to account for the climate effects of methane hydrate development without dictating technological outcomes or national energy priorities. Additionally, if natural gas truly is intended as a bridge fuel to a renewable energy future, nations engaged in methane hydrate development also should prepare concrete plans for transitioning beyond natural gas to renewable energy systems.

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[176] *See, e.g.*, Mann, *supra* note 172, at 63.

[177] *See id.* at 62 ("[F]ixing leaks is a task that developed nations can accomplish[.]").

[178] NRC, REALIZING THE ENERGY POTENTIAL OF METHANE HYDRATE, *supra* note 167, at 135–36 (making recommendations to compile existing information regarding drilling experience in areas with methane hydrates and to evaluate geohazards and environmental issues specific to methane production from such areas).

[179] *Cf.* Adam Briggle, *It's Time to Frack the Innovation System*, SLATE (Apr. 11, 2012, 7:00 AM), http://www.slate.com/articles/technology/future_tense/2012/04/george_p_mitchell_fracking_and_scientific_innovation_.html (arguing that shale gas R&D was assessed only for technical feasibility and economic profitability, and that "innovators failed to consider questions about how the technologies would play out in the real world").

[180] *See* Krey et al., *supra* note 165, at 5 (recommending integration of agendas of energy security and climate change).

B. Algal Biofuel

Just as methane hydrate technology represents a potential successor to slickwater fracturing, algal biofuel represents a possible successor to corn ethanol. Unlike methane hydrates, algal biofuel offers the prospect of drastically reducing carbon emissions. This does not mean that algal biofuels would be free of environmental hazards, however.

Using sunlight, carbon dioxide, and water, algae produce oils that can be converted to biodiesel, gasoline, and other types of fuel.[181] Several characteristics make algae attractive as a potential source of biofuels, including their photosynthetic productivity, which is higher than that of terrestrial plants; their ability to grow on non-arable lands and rely on water sources other than freshwater, including wastewater; and the relative ease with which carbon stored within algae can be converted into fuel as compared to the lignocelluloses used to generate cellulosic biofuels.[182]

There are two basic methods for growing algae: (1) open-pond cultivation, a technique commonly used today to produce algal neutraceuticals; and (2) closed-system cultivation in photobioreactors, transparent containers with large surface areas that maximize the light available for photosynthesis.[183] Open-pond systems are simpler in design and generally less costly to build and operate.[184] These advantages make them easier to scale up and have led some to assume that open-pond cultivation will be "more likely to achieve the goal of technoeconomic feasibility for producing microalgae for biofuels."[185] But open-pond systems are less productive, require more water, and ultimately offer a less stable growing environment than closed systems.[186] They also pose a greater potential for contaminating the external environment or becoming contaminated themselves.[187]

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[181] KELSI BRACMORT, CONG. RESEARCH SERV., R42122, ALGAE'S POTENTIAL AS A TRANSPORTATION BIOFUEL 4 (2013); *see also* D. Ryan Georgianna & Stephen P. Mayfield, *Exploiting Diversity and Synthetic Biology for the Production of Algal Biofuels*, 488 NATURE 329, 329 (2012).

[182] NAT'L RESEARCH COUNCIL, SUSTAINABLE DEVELOPMENT OF ALGAL BIOFUELS IN THE UNITED STATES 4–5, 27–28 (2012) [hereinafter NRC, ALGAL BIOFUELS]; Georgianna & Mayfield, *supra* note 181, at 329. Other microorganisms being explored as potential biofuel producers include yeast and bacteria. *See* Michael S. Ferry et al., *Synthetic Biology Approaches to Biofuel Production*, 3 BIOFUELS 9, 11 (2012).

[183] NRC, ALGAL BIOFUELS, *supra* note 182, at 42–53.

[184] *Id.* at 50–53; Georgianna & Mayfield, *supra* note 181, at 329.

[185] NRC, ALGAL BIOFUELS, *supra* note 182, at 51.

[186] *Id.* at 50–51; Georgianna & Mayfield, *supra* note 181, at 330.

[187] NRC, ALGAL BIOFUELS, *supra* note 182, at 51–52.

Production of algal biofuels is technically feasible in open or closed systems, but commercialization remains a long way off. Algal biofuel projects are presently confined to research labs and pilot production plants.[188] Using existing technologies, algal biofuel production yields a low energy return on investment, consumes large quantities of water and nutrients, and is not cost-competitive with ordinary gasoline.[189] Although algal biofuels qualify as advanced biofuels under the 2007 RFS,[190] cellulosic ethanol technology is further along and better positioned to capture the advanced biofuels market.[191] Improvements in algal strains and in cultivation and processing methods will be necessary in order for algal biofuels to play a significant role in satisfying energy needs.[192] These improvements will likely rely on genetic engineering and synthetic biology techniques to create algae that are more productive and tolerant of different environmental conditions.[193] DOE has set a goal of producing cost-competitive algal biofuels by 2022,[194] but many experts predict that such a goal will not be achieved until after 2030.[195]

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[188] BRACMORT, *supra* note 181, at 11.

[189] NRC, ALGAL BIOFUELS, *supra* note 182, at 2–3, 99; Robert F. Service, *Algae's Second Try*, 333 SCIENCE 1238, 1238–39 (2011) (reporting estimate by National Renewable Energy Laboratory scientists that the cheapest algal fuels cost $2.25 per liter, approximately double the price of gasoline).

[190] *See* BRACMORT, *supra* note 181, at 2–3; CONG. RESEARCH SERV., REPORT R40155, RENEWABLE FUEL STANDARD (RFS), *supra* note 68, at 4–5. The Energy Independence and Security Act of 2007, which created the RFS2 mandate, defines "advanced biofuel" as a renewable fuel "other than ethanol derived from cornstarch," having 50 percent lower lifecycle GHG emissions relative to gasoline. 42 U.S.C. § 7545(o)(1)(B)(i) (2006); Energy Independence and Security Act of 2007, Pub. L. No. 110-140, § 201(1)(B)(i), 121 Stat. 1519 (2007).

[191] *See* BRACMORT, *supra* note 181, at 13–14 (noting that there are no commercial-scale algal biofuel plants); Service, *supra* note 60, at 1374 (mentioning construction of various cellulosic ethanol plants). Cellulosic ethanol also benefits from statutory mandates that favor it over other advanced biofuels, see 42 U.S.C. § 7545(o)(2)(B)(i)(III) (establishing specific volumetric mandates for cellulosic biofuel), but even that technology has not matured fast enough to keep pace with these mandates. *See* Service, *supra* note 60, at 1375.

[192] NRC, ALGAL BIOFUELS, *supra* note 182, at 6; Georgianna & Mayfield, *supra* note 181, at 330–33.

[193] *See* NRC, ALGAL BIOFUELS, *supra* note 182, at 36–41; Georgianna & Mayfield, *supra* note 181, at 331 (noting the "strong push in most biofuel research towards molecular and transgenic technologies rather than breeding"); Service, *supra* note 189, at 1239 (describing use of synthetic biology techniques in algal biofuel research).

[194] U.S. Dep't of Energy, *Secretary Moniz Announces New Biofuels Projects to Drive Cost Reductions, Technological Breakthroughs*, ENERGY.GOV (Aug. 1, 2013, 2:00 PM), http://energy.gov/articles/secretary-moniz-announces-new-biofuels-projects-drive-cost-reductions-technological.

[195] *See, e.g.*, Giulia Fiorese et al., *Advanced Biofuels: Future Perspectives From an Expert Elicitation Survey*, 56 ENERGY POL'Y 293, 302 (2013); *see also* David Biello, *Can Algae Feed the World and Fuel the Planet? A Q&A With Craig Venter*, SCI. AM. (Nov. 15, 2011), http://www.scientificamerican.com/article.cfm?id=can-algae-feed-the-world-and-fuel-the-planet (characterizing algal biofuel efforts as "a long-term plan"); Andrew Herndon, *Exxon Refocusing Algae Biofuels Program After $100 Million Spend*, BLOOMBERG (May 20, 2013), http://www.bloomberg.com/news/print/2013-05-21/exxon-

Algal biofuels have a number of environmental concerns associated with them, including water consumption, surface and groundwater contamination, and unintended releases of algae.[196] If algae are cultivated in open ponds, for example, water consumption could exceed the total quantity of water presently used for irrigated agriculture, and water used in cultivation could contaminate drinking water supplies.[197] Moreover, releases of algae to natural environments could disrupt ecosystems.[198] Such releases, which could occur through air, water, boats, or animal vectors, are "expected to be common" if cultivation takes place in open ponds.[199] Adopting closed cultivation systems and using noninvasive and less noxious algae species could reduce the frequency of releases and resulting hazards.[200]

Novel hazards may be more common among algal strains that are produced through genetic engineering or synthetic biology.[201] Engineered microorganisms may have higher evolution rates, and such microorganisms that escape may exchange novel genetic sequences with other organisms, resulting in unexpected effects on the environment.[202] Evaluating the environmental hazards posed by genetically engineered algae "will be a complex undertaking, given the diversity of organisms, range of engineered functions, and range of environments potentially receiving the engineered organisms."[203] Strains engineered to grow vigorously might pose greater risks to natural environments, for instance, whereas other strains may be less suited to survive or reproduce outside controlled conditions.[204]

Relevant public investments and policies should consider the potential for algal biofuel to disrupt existing energy systems and the types of hazards that widespread deployment might create. Broad adoption of advanced biofuels would not require restructuring of existing transportation systems or significant lifestyle changes.[205] Advanced biofuels will nonetheless likely encounter resistance from incumbent players engaged in the production, distribution,

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refocusing-algae-biofuels-program-after-100-million-spend.html (reporting Exxon projections "that its investments in algae biofuels may not succeed for at least another 25 years").

[196] NRC, ALGAL BIOFUELS, *supra* note 182, at 106–10, 140–44.

[197] *Id.* at 106–07, 140–41.

[198] *Id.* at 162.

[199] *Id.* at 160–61.

[200] *Id.* at 161–62.

[201] *Id.* at 168–69.

[202] Genya V. Dana et al., *Four Steps to Avoid a Synthetic-Biology Disaster*, 483 NATURE 29, 29 (2012).

[203] NRC, ALGAL BIOFULES, *supra* note 182, at 168.

[204] *See id.* at 169.

[205] *See* WEISS & BONVILLIAN, *supra* note 15, at 97–98 (describing biofuels as an example of a "secondary" technology that would substitute for a component in existing energy-use systems); Fiorese et al., *supra* note 195, at 293 (observing that biofuels "do not require substantial changes in car engines, nor in the re-fuelling process").

and use of rival transportation fuels, namely, petroleum and corn ethanol.[206] Granted, some established players may position themselves to profit from a transition to biofuels. Exxon Mobil, for example, has invested more than $100 million in algal biofuel research and development thus far.[207] Such investments have shrunk in the wake of slow progress, however, and are dwarfed by expenditures on development of conventional oil sources.[208] In fact, major oil companies have lobbied to weaken the renewable fuel mandates that prompted initial industry interest in biofuels.[209]

In light of the long timeline to economic viability and the potential disruption that advanced biofuels pose to existing energy systems, private sector investment likely will remain modest. The commercial success of algal biofuel will require government support, whether in the form of direct research investment or biofuel mandates. The extent to which government should single out algal biofuels for support nonetheless remains an open question. Entrenched policies promoting corn ethanol illustrate the danger that industry-specific enactments will favor politically powerful constituencies regardless of policy objections. The 2007 RFS, which recognizes the environmental superiority of advanced biofuels over corn ethanol, is a step in the right direction.[210] It is arguably flawed, however, in that it favors cellulosic biofuels over other advanced biofuels, though these other biofuels may be environmentally preferable in some instances.[211] Nonetheless, setting a renewable fuels standard that provides long-term certainty is essential

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[206] *See* WEISS & BONVILLIAN, *supra* note 15, at 105 (noting oil industry concern about shift to biofuels as well as potential for farm sector to oppose shift away from corn ethanol).

[207] Herndon, *supra* note 195.

[208] *See* Ken Wells, *Big Oil's Big in Biofuels*, BLOOMBERG BUSINESSWEEK (May 10, 2012), http://www.businessweek.com/articles/2012-05-10/big-oils-big-in-biofuels; Herndon, *supra* note 195.

[209] Ben Elgin & Peter Waldman, *Chevron Defies California on Carbon Emissions*, BLOOMBERG (Apr. 18, 2013), http://www.bloomberg.com/news/2013-04-18/chevron-defies-california-on-carbon-emissions.html.

[210] *See* Powers, *supra* note 66, at 699–700 (noting that 2007 RFS mandates production of advanced biofuels and defines biofuels according to their lifecycle GHG emissions).

[211] More generally, the RFS is a less direct instrument than a carbon tax for reducing GHG emissions because the climate effect of biofuels, including advanced biofuels, depends on production processes, land use changes, and other factors. NAT'L RES. COUNCIL, RENEWABLE FUEL STANDARD: POTENTIAL ECONOMIC AND ENVIRONMENTAL EFFECTS OF U.S. BIOFUEL POLICY 4–5 (2011) [hereinafter NRC, RENEWABLE FUEL STANDARD]; *see* Daniel A. Farber, *Indirect Land Use Change, Uncertainty, and Biofuels Policy*, 2011 U. ILL. L. REV. 381, 409 (urging careful design of biofuels mandates to account for indirect land use change); Madhu Khanna et al., *Land Use and Greenhouse Gas Mitigation Effects of Biofuel Policies*, 2011 U. ILL. L. REV. 549, 580 (concluding that "supplementing the RFS with a price on all fuels based on their GHG intensity raises social welfare above the level with the RFS alone and lowers GHG intensity and overall fuel consumption"). For a critical analysis of specific provisions of the 2007 RFS, see Powers, *supra* note 66, at 699–707.

to long-term technology investment.[212] It also guarantees a market for new technologies that would otherwise face intense pressure from market incumbents.[213]

As with other new technologies, society will need to watch for adverse effects from algal biofuels. But the long lead time anticipated before commercial viability suggests that there will be opportunities to study such effects and develop mechanisms to ameliorate or avoid them. Indeed, we already know some of the potential hazards and effective countermeasures. Cultivation of algae in closed systems would address many hazards, particularly the possibility of escape and ecological disruption. Closed-system cultivation may also alleviate public concerns regarding the use of genetically engineered algae.[214] With these considerations in mind, researchers and policymakers might adopt voluntary guidelines favoring physical containment.[215] Under such guidelines, algal biofuel projects would employ physical containment, except when scientists affirmatively find that the strains at issue pose little risk to the environment. These guidelines could be incorporated into scientific research efforts as well as economic models evaluating the commercial viability of algal fuels. Accordingly, scientists might focus their efforts on improving yields from algae that grow in contained environments and on reducing the costs and energy demands associated with closed systems.

Finally, public resistance in some quarters to genetically modified organisms as well as to renewable energy technologies suggests the need for public input and outreach as algal biofuel development proceeds. Genetic engineering has generated controversy in the United States and other countries, where food

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[212] *See* Bracmort, *supra* note 181, at 13; Alexandra B. Klass, *Tax Benefits, Property Rights, and Mandates: Considering the Future of Government Support for Renewable Energy*, at 27–28 (2013), *available at* http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2222987. The history of algal biofuel research illustrates the difficulties caused by uncertain support. DOE's Aquatic Species Program, launched in the wake of the 1970s energy crisis, built a collection of oil-producing algae and sought to demonstrate the feasibility of large-scale cultivation, but was ended by Congress in 1996. *See* NRC, ALGAL BIOFUELS, *supra* note 182, at 11–12; Service, *supra* note 189, at 1238; *see also* NAT'L RENEWABLE ENERGY LAB'Y, A LOOK BACK AT THE U.S. DEPARTMENT OF ENERGY'S AQUATIC SPECIES PROGRAM: BIODIESEL FROM ALGAE (1998), *available at* http://www.nrel.gov/biomass/pdfs/24190.pdf.

[213] *See* NRC, RENEWABLE FUEL STANDARD, *supra* note 211, at 3.

[214] *Cf.* NRC, ALGAL BIOFUELS, *supra* note 182, at 170–71 (discussing social acceptability of genetically engineered algae).

[215] Principles and recommendations adopted by recombinant DNA researchers during the 1970s provide an example of how voluntary guidelines can steer research activities in the face of uncertain risks. *See* Paul Berg et al., *Summary Statement of the Asilomar Conference on Recombinant DNA Molecules*, 72 PROC. NAT'L. ACAD. SCI. 1981 (1975). Although the process that generated those principles was problematic, the principles proved influential. *See* SHEILA JASANOFF, DESIGNS ON NATURE: SCIENCE AND DEMOCRACY IN EUROPE AND THE UNITED STATES 46–48 (2005); LIN, *supra* note 3, at 52–54.

applications have encountered especially strong resistance.[216] Moreover, public attitudes toward renewable energy are somewhat divided along political lines, and government support for biofuels sometimes has been subject to partisan attack.[217] Whether synthetic or genetically engineered algae will stir up controversy remains to be seen, as public awareness of advanced biofuels is relatively low. In deciding how to proceed in this area, policymakers should take into account public values as well as the views of technical experts.

C. Nanosolar

Despite substantial growth in recent years, solar energy accounts for only 0.1 percent of electricity generation in the United States.[218] Solar energy faces several important technical challenges. First, solar cells are relatively inefficient in converting the sun's energy into electricity.[219] Second, despite recent reductions in the cost of installed solar energy systems, solar cells remain expensive to manufacture and install.[220] The combined effect of solar cells' low efficiency and high upfront costs is that solar energy remains significantly more expensive than energy produced from fossil fuels.[221] Third, if broad adoption of solar energy is to occur, efficient energy storage ranging from large-grid-scale storage to smaller-scale distributed storage must be developed to accommodate the intermit-

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[216] *See also* Martin W. Bauer, *Distinguishing* Red *and* Green *Biotechnology: Cultivation Effects of the Elite Press*, 17 INT'L J. PUB. OPINION RES. 63, 66–67 (2005) (distinguishing between "green," food-related genetic engineering applications, which have encountered greater controversy, and "red" biomedical applications); Andrew W. Torrance, *Intellectual Property as the Third Dimension of GMO Regulation*, 16 KAN. J.L. & PUB. POL'Y 257, 257 (2007).

[217] Michael A. Cacciatore et al., *Public Attitudes Toward Biofuels*, 31 POL. & LIFE SCI. 36, 37–38, 47 (2012).

[218] U.S. Energy Info. Admin., *What is U.S. Electricity Generation by Energy Source?*, http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3 (last updated May 9, 2013).

[219] Efficiency figures for the most commonly used solar cells typically do not exceed 25 percent. *See Solar Energy:Stacking the Deck*, ECONOMIST, Feb. 22, 2014, http://www.economist.com/news/science-and-technology/21596924-way-double-efficiency-solar-cells-about-go-mainstream-stacking. Somewhat higher efficiency figures have been achieved under certain experimental conditions. *See* Martin A. Green et al., *Solar Cell Efficiency Tables (Version 39)*, 20 PROGRESS PHOTOVOLTAICS: RES. & APPLICATIONS 12, 13–16 (2011).

[220] *See* GALEN BARBOSE ET AL., TRACKING THE SUN VI: AN HISTORICAL SUMMARY OF THE INSTALLED PRICE OF PHOTOVOLTAICS IN THE UNITED STATES FROM 1998 TO 2012, at 43 (2013).

[221] *See* Stefan Reichelstein & Michael Yorston, *The Prospects for Cost Competitive Solar PV Power*, 55 ENERGY POL'Y 117, 126 (2013); *see also* K. Branker et al., *A Review of Solar Photovoltaic Levelized Cost of Electricity*, 55 RENEWABLE & SUSTAINABLE ENERGY REVS. 4470, 4472–74 (2011) (reviewing various estimates of levelized cost of electricity generation for solar photovoltaics).

tent nature of solar energy.[222] Such storage, however, is not yet readily available. Advances in nanotechnology, however, offer the promise of helping to address each of these challenges.

The amount of electricity produced when photovoltaic (PV) solar cells convert photons into electric current depends on the number of electrons that pass between layers of semiconductor material.[223] Incorporation of nanotechnology into PV cells can increase efficiency in several ways.[224] For instance, dye-sensitized solar cells containing a porous layer of titanium dioxide nanomaterials provide a greater surface area than conventional silicon PV materials and therefore can absorb more light.[225] In addition, semiconductor nanoparticles known as quantum dots emit multiple electrons for each photon absorbed and can be fine-tuned in size to absorb different wavelengths of light.[226] Apart from increasing efficiency, nanotechnology can decrease capital costs. For example, thin film solar cells can be manufactured and installed more cheaply than conventional crystalline semiconductor cells.[227] Nanomaterials likewise could be critical to improving energy storage and release in rechargeable batteries as well as supercapacitors.[228]

Some nanosolar applications, such as thin film solar cells, are already on the market.[229] Many other applications, however, are only at the early stages of research.[230] Like other emerging technologies, nanosolar faces a number of hurdles that must be overcome before commercialization. Such hurdles in-

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[222] *See* Z. Abdin et al., *Solar Energy Harvesting With the Application of Nanotechnology*, 26 RENEWABLE & SUSTAINABLE ENERGY REVS. 837, 843 (2013).

[223] *See* Elena Serrano et al., *Nanotechnology for Sustainable Energy*, 13 RENEWABLE & SUSTAINABLE ENERGY REVS. 2373, 2375 (2009).

[224] David J. Hess & Anna Lamprou, *Nanotechnology and the Environment*, *in* NANOTECHNOLOGY AND GLOBAL SUSTAINABILITY 21, 27–28 (Donald Maclurcan & Natalia Radywyl eds., 2012).

[225] *See* Vladan Mlinar, *Engineered Nanomaterials for Solar Energy Conversion*, 24 NANOTECHNOLOGY Jan. 8, 2013, at 1, 8 ("Understanding how to engineer nanomaterials for targeted solar-cell applications is the key to improving their efficiency. . . ."); Serrano et al., *supra* note 223, at 2376; Duncan Graham-Rowe, *Can Nanotechnology Provide Cheaper Solar Energy?*, GUARDIAN (Sept. 20, 2011, 2:28 PM), http://www.theguardian.com/nanotechnology-world/can-nanotechnology-provide-cheaper-solar-energy; *see also* Patrick J. Kiger, *Sun Plus Nanotechnology: Can Solar Energy Get Bigger by Thinking Small?*, NAT'L GEOGRAPHIC NEWS (Apr. 28, 2013), http://news.nationalgeographic.com/news/energy/2013/04/130429-nanotechnology-solar-energy-efficiency (briefly surveying various nanotechnology innovations that could improve solar energy performance).

[226] Abdin et al., *supra* note 222, at 847–48; Serrano et al., *supra* note 223, at 2375.

[227] Danail Hristozov & Jürgen Ertel, *Nanotechnology and Sustainability: Benefits and Risks of Nanotechnology for Environmental Sustainability*, 22 FORUM DER FORSCHUNG 161, 164 (2009) (noting in addition that thin film cells are generally less efficient).

[228] Abdin et al., *supra* note 222, at 843–44; Serrano et al., *supra* note 223, at 2380–81.

[229] Hristozov & Ertel, *supra* note 227, at 164.

[230] Hema Ramsurn & Ram B. Gupta, *Nanotechnology in Solar and Biofuels*, 1 ACS SUSTAINABLE CHEMISTRY & ENGINEERING 779, 793 (2013).

clude poor control of the size and placement of nanoscale features, short lifetimes, and high manufacturing costs.[231] Experts anticipate some progress on these fronts in the coming decade, though perhaps not enough for nanosolar to achieve commercial viability.[232] Indeed, because nanosolar and solar energy systems in general could be especially disruptive to existing energy systems, government support will be essential for their success.

The use of nanomaterials nonetheless raises health and environmental concerns. Scientists have begun to document potential hazards and have found evidence of toxicity for some nanomaterials, including titanium dioxide nanoparticles and carbon nanotubes.[233] Both of these materials are used in certain nanosolar applications.[234] This area is filled with uncertainty, however, especially as risk levels appear to vary with the identity of each substance, as well as nanoparticle size, shape, method of manufacture, presence of impurities, nature of surface coatings, and degree of aggregation.[235]

Even with the uncertainty surrounding the exact risks posed by nanomaterials, we should not allow it to serve as an excuse for inaction in managing risks. As with various emerging energy technologies of the past, there is information about potential hazards sufficient to develop precautionary measures. Treating nanomaterials as if they are hazardous—unless proven otherwise—would go a long way toward promoting truly sustainable nanosolar technologies by helping to reduce or control as yet unidentified hazards.[236] To reduce the likelihood of exposure and release during use, many potential nanosolar applications can be embedded in a matrix structure and contained within sealed solar panels or batteries.[237] In contrast, contemplated

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[231] NSTC COMM. ON TECHN., NANOTECHNOLOGY FOR SOLAR ENERGY COLLECTION AND CONVERSION 1–3 (2010), *available at* http://www.nano.gov/sites/default/files/pub_resource/nnisiginitsolarenergyfinaljuly2010.pdf.

[232] *See id.* at 3–4.

[233] *See* Aasgeir Helland et al., *Reviewing the Environmental and Human Health Knowledge Base of Carbon Nanotubes*, 115 ENVTL. HEALTH PERSP. 1125 (2007); T. Kato et al., *Genotoxicity of Multi-Walled Carbon Nanotubes in Both In Vitro and In Vivo Assay Systems*, 7 NANOTOXICOLOGY 452–61 (2013); P. A. Schulte et al., *Occupational Exposure Limits for Nanomaterials: State of the Art*, 12 J. NANOPARTICLE RES. 1971, 1977–78 (2010); Benedicte Trouiller et al., *Titanium Dioxide Nanoparticles Induce DNA Damage and Genetic Instability* In vivo *in Mice*, 69 CANCER RES. 8784, 8788 (2009).

[234] *See* Abdin et al., *supra* note 222, at 844, 847; Serrano et al., *supra* note 223, at 2376, 2381.

[235] Helland et al., *supra* note 233, at 1129–30. *See also* Shahriar Sharifi, *Toxicity of Nanomaterials*, 41 CHEM. SOC. REV. 2323, 2338 (2012).

[236] *Cf.* Graham-Rowe, *supra* note 225 (stating that treating nanoparticles as hazardous materials can avoid "unpleasant surprises in the years to come").

[237] Hess & Lamprou, *supra* note 224, at 33 ("Assuming that nanosolar materials are embedded in matrices or grown in a substrate, those hazards and risks would likely be concentrated in the workplace . . . and in disposal sites . . . .").

applications such as the use of nanosprays to turn windows into PV generators are likely to release nanomaterials into the environment.[238] A precautionary approach would favor those applications that minimize the release of nanomaterials into the environment. In addition, even where nanomaterials are contained, careful product design can minimize accidental nanomaterial releases.

Potential environmental hazards at other stages of the product life cycle, particularly during research, manufacturing, and disposal, warrant further attention.[239] In some instances, there may be sufficient data to develop benchmark occupational exposure levels for categories of nanomaterials.[240] Eventually, these exposure levels may be refined in specific contexts and revised as further information becomes available.[241] Until suitable benchmark levels can be developed, experts recommend precautionary measures to reduce the potential hazards of laboratory or occupational exposure to nanomaterials.[242] These measures include the design of nanomaterials and production processes, installation of engineering controls, use of personal protective equipment, and monitoring of employee health.[243]

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[238] *See* Hess & Lamprou, *supra* note 224, at 32.

[239] *See* P.A. Schulte et al., *Overview of Risk Management for Engineered Nanomaterials*, 429 J. PHYSICS: CONFERENCE SERIES, Apr. 2013, at 4–6 (identifying workplace environments where exposure to engineered nanomaterials may occur).

[240] *See* Schulte et al., *supra* note 233, at 1977–84 (sketching out such an approach); *see also* Eileen D. Kuempel et al., *Risk Assessment and Risk Management of Nanomaterials in the Workplace: Translating Research to Practice*, 56 ANNALS OCCUPATIONAL HYGIENE 491 (2012) (discussing current hazard and exposure data for nanomaterials as well as research gaps). Traditionally, risk assessors estimated a "No Observed Adverse Effect Level" at which there are no statistically significant adverse effects from exposure to a chemical substance. Risk assessors increasingly use the benchmark dose approach, which focuses on increases in adverse effects as a result of changes in exposure, as an alternative way to analyze and characterize chemical risk. Guidance of the Sci. Comm., European Food Safety Auth., *Use of the Benchmark Dose Approach in Risk Assessment*, THE EFSA JOURNAL 1-72, 5-72, 9-72 to 14-72 (2009) *available at* http://www.efsa.europa.eu/de/scdocs/doc/1150.pdf.

[241] *Cf.* Kuempel et al., *supra* note 240, at 492 (noting that few occupational exposure levels have been developed for nanomaterials and that none of these are regulatory standards).

[242] *See, e.g.*, NAT'L INST. FOR OCCUPATIONAL SAFETY & HEALTH, APPROACHES TO SAFE NANOTECHNOLOGY: MANAGING THE HEALTH AND SAFETY CONCERNS ASSOCIATED WITH ENGINEERED NANOMATERIALS (2009); SAFE WORK AUSTRALIA, ENGINEERED NANOMATERIALS: FEASIBILITY OF ESTABLISHING EXPOSURE STANDARDS AND USING CONTROL BANDING IN AUSTRALIA 27–35 (2010) (discussing control banding approach); Marilyn F. Hallock et al., *Potential Risks of Nanomaterials and How to Safely Handle Materials of Uncertain Toxicity,* 16 J. CHEMICAL HEALTH & SAFETY 16, 19 (2009); Schulte et al., *supra* note 239.

[243] NAT'L INST. FOR OCCUPATIONAL SAFETY & HEALTH, *supra* note 242, at 35–54; Schulte et al., *supra* note 239, at 6–7; *see also* Hallock et al., *supra* note 242, at 20–21 (discussing best practices for university research laboratories). Green chemistry principles sometimes may be applied to encourage use of sustainably designed nanomaterials made from renewable ingredients or coated so that they

Finally, disposal of solar PV cells, including nanosolar PV cells, merits careful oversight. Solar PV cells generally contain hazardous substances, including lead and cadmium, which can be released when PV cells are disposed in a landfill or incinerator.[244] Solar PV cells that incorporate nanomaterials may exacerbate hazardous risks. Existing law, however, allows most discarded solar panels to be disposed of as ordinary waste.[245] A more environmentally sustainable approach would subject PV manufacturers and distributors to an extended producer-responsibility scheme.[246] Such a scheme, which could incorporate mandatory or voluntary recycling, would encourage greener design of PV cells.[247] A voluntary scheme could encourage participation by offering liability protection contingent on adopting and successfully implementing a take-back program.

Ultimately, the use of nanomaterials could lead to important advances in solar energy and storage. Substantial government involvement and oversight will be needed, however, to ensure that these advances occur in an environmentally sound manner.

D. Summing Up

Methane hydrates, algal biofuels, and nanosolar all offer the prospect of supplying significant portions of our energy needs in the future. At present, however, none of these technologies is cost-competitive with existing energy sources, and each faces considerable obstacles to commercialization. Although the measured pace of energy technology development frustrates efforts to transition rapidly from fossil fuels to renewables, it also provides an opportunity for policymakers to steer that development to reduce or avoid problems that such technologies may create. For methane hydrates, policymakers can explore

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remain relatively inert if released into the environment. Lynn L. Bergeson, *Sustainable Nanomaterials: Emerging Governance Systems*, 1 ACS SUSTAINABLE CHEMICAL ENGINEERING 724, 725 (2013).

[244] *See* Vasilis M. Fthenakis, *Overview of Potential Hazards*, *in* SOLAR CELLS: MATERIALS, MANUFACTURE AND OPERATION 533, 542–43 (Augustin Joseph McEvoy et al. eds., 2d ed. 2013).

[245] Genevieve Coyle, Comment, *The Not-So-Green Renewable Energy: Preventing Waste Disposal of Solar Photovoltaic (PV) Panels*, 4 GOLDEN GATE U. ENVTL. L.J. 329, 343–48 (2011) (analyzing potential applicability of federal and state laws to disposal of solar panels). California's proposed regulations to subject all discarded PV modules to the handling and treatment requirements governing electronic waste were disapproved by the State's Office of Administrative Law in part because they would have exempted PV cells that do qualify as hazardous waste from hazardous waste law requirements. *See* STATE OF CAL. OFFICE OF ADMIN. LAW, OAL FILE NO. 2013-0819-03S, DECISION ON DISAPPROVAL OF REGULATORY ACTION (Oct. 8, 2013), *available at* http://www.dtsc.ca.gov/LawsRegsPolicies/Regs/upload/DTSC-disapproval-decision.pdf.

[246] *See* Coyle, *supra* note 245, at 352–59.

[247] *See id.* at 353.

methods to reduce methane leakage or perhaps even discourage methane hydrate use. For algal biofuels, policymakers can support the development of closed algal systems rather than open systems. And for nanosolar, policymakers can encourage applications that are less likely to release nanomaterials into the environment. Public investment will be critical for the successful development of new energy technologies, and such investment should be directed to foster public ends.

CONCLUSION

The preceding discussion offers several guiding principles for carrying out technology assessment of emerging energy technologies. First, assessment of emerging energy technologies is feasible, as the case studies of existing energy technologies demonstrate. Energy technologies develop gradually, and many of their effects are identifiable. Nuclear energy, corn ethanol, and hydraulic fracturing took decades to achieve commercialization, and their environmental effects could have been anticipated, at least in part. Technology assessment cannot be taken for granted, however. Society must devote sufficient time and resources to analyzing the effects of emerging technologies in a deliberate and ongoing process that involves the public.

Second, efforts to carry out technology assessment and make use of its results will have to contend with powerful counterforces from industry and other vested interests. Dominant energy technologies have become entrenched notwithstanding serious concerns, and nanosolar, advanced biofuels, and other emerging energy technologies that threaten to disrupt existing energy structures may require particular attention and support. The common admonition against picking technology winners is a worthwhile warning against allowing vested interests to have undue influence on relevant laws and policies. If technology assessment is to have any substantial value, however, the information it generates should inform policy choices. Using the information we have to pick the right winners simply makes sense.

Finally, government support for technology development, not just basic research, is essential to bring new energy technologies to fruition. At the least, the government should be more supportive of disruptive technologies that promise to achieve social goals and more skeptical of technologies that complement entrenched systems. Through active oversight and support, government can steer the difficult, dangerous, and essential process of energy innovation.