Technology in Society 32 (2010) 65–71

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Ethanol's most recent breakthrough in the United States: A case of socio-technical transition

Michael S. Carolan*

Department of Sociology, B246Clark, Colorado State University, Fort Collins, CO 80523-1784, United States

Keywords:
Automobiles
Biofuels
Ethanol
Path dependency
Science and technology studies
Socio-technical system
Technological change

A B S T R A C T

Applying insights from the field of science and technology studies (STS), this paper helps explain the meteoric rise of ethanol in recent years in the United States. The term *socio-technical system* is a conceptual reminder that technologies affect and are an effect of their broader infrastructural, organizational, regulatory, and symbolic environments. As explained, there was no single "cause" driving this transition. Rather, dynamics at different levels came together and reinforced each other. When taken together, these transitions had the cumulative effect of propelling the ethanol juggernaut to the heights of today. The author analytically breaks down the automobile socio-technical system and examines transitions that occurred in its various dimensions. While not predictive, the socio-technical framework reminds us of influential path-dependent logics. The paper concludes with a brief discussion of where, in light of these realities, the biofuels trajectory may be headed in the not-too-distant future.

1. Introduction

The meteoric rise in the use of ethanol over the last three decades in the United States is remarkable. In 1980, 175 million gallons of ethanol were produced. That figure increased to 900 million gallons by 1990, to 1.63 billion gallons by 2000, and by 2007, output topped 6.5 billion gallons [1]. Future output levels look to mirror recent trends. In this 2007 State of the Union address, former President Bush called for the production of 35 billion gallons of ethanol by 2017.

What happened to cause this huge spurt in production? Ethanol's benefit as a fuel additive has long been known; Henry Ford was an early proponent of this biofuel [2]. While ethanol experienced a surge of interest in the early decades of the twentieth century and again briefly in the 1970s, what caused the tide to turn so favorably in recent years? Applying insights from the field of science and technology studies (STS), this paper helps explain the so-called "ethanol juggernaut" [3] currently underway.

The term *socio-technical system* is a conceptual reminder that technologies affect and are an effect of their broader infrastructural, organizational, regulatory, and symbolic environments [see, for example, 4–8]. It would therefore be naive to attribute all of ethanol's recent success to, say, a powerful corn lobby, rising petroleum prices, and/or an overzealous government looking for a quick fix from what is often called our "addiction to oil."

The factors underlying ethanol's strong position come from a host of sources, and a socio-technical system perspective allows us to unravel some of this complexity. As a heuristic, Fig. 1 identifies ten analytic categories of the (gasoline) automobile socio-technical system. These categories are examined in the pages that follow, to help make sense of the

* Tel.: +1 970 491 5797; fax: +1 970 491 2191.
E-mail address: mcarolan@colostate.edu

0160-791X/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.techsoc.2010.04.003

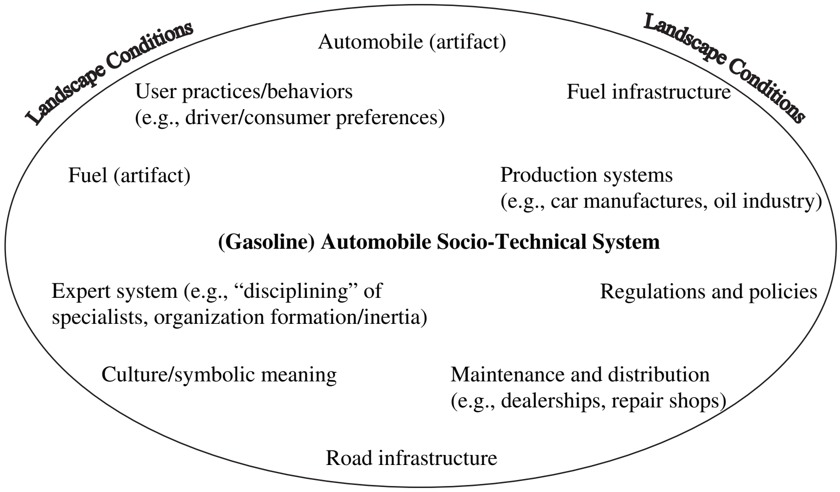

Fig. 1. Socio-technical system for the gasoline automobile.

unprecedented growth in the production and consumption of ethanol. In addition, Fig. 1 notes “landscape conditions.” This is to acknowledge the influence of broader geopolitical conditions on the socio-technical system under investigation [7]. These factors are also incorporated into the following analysis.

Today’s ethanol boom represents a transition in the automobile socio-technical system rather than the emergence of anything new. Indeed, part of ethanol’s success can be attributed to how well it fits within existing dimensions of the pre-existing system. To explain this, I go back a few decades to a period that, in hindsight, served an important incubation function for ethanol. The 1990s created openings for ethanol use that greatly reduced the social and economic transaction costs of producing and consuming this fuel. These openings came as transitions within particular dimensions (detailed in Fig. 1) of the automobile socio-technological system. This had a cascade effect. Socio-technical openings helped to beget further socio-technical openings, which, in combination with broader landscape changes, brought the system to its current position. In other words, a socio-technical shift of the magnitude needed to explain ethanol’s current position only occurs after multiple dimensions of the system have already been altered. This shift was not inevitable. Only with the benefit of hindsight can I stitch together what seems to be a seamless narrative. While not predictive, the socio-technical framework also reminds us of the influential structural realities (“lock-in”) that help guide the path of systems. The paper concludes with a brief discussion of where, in light of these realities, the ethanol juggernaut may be headed unless these logics are disrupted.

2. Regulation and policies: an incubation space for ethanol

Significant pro-ethanol legislation and regulation emerged in the 1970s [9]. For purposes of brevity, however, I begin this analysis in the early 1990s. (To cover the entire US history of ethanol legislation, both pro and con, would take us back to the Revenue Act of 1862, when a “sin tax” was placed on both industrial and potable alcohol [10]). The early 1980s saw a retraction of some earlier established pro-ethanol legislation, thanks in large part to the free market ideology of the Reagan administration [9]. Even so, ethanol continued to be produced, spurred on by US-supported loans. For example, in 1980 the Energy Security Act provided insured loans for up to 90% of construction costs on ethanol plants [11] and corn subsidies.

Early pro-ethanol policies provided the industry important “incubation” space that helped shield the fuel from market forces. As others have noted, non-mainstream technological artifacts often require protection from market signals if they are to ever become a formidable threat to the dominant socio-technical system [12]. This “protection is needed because new technologies initially have low price/performance ratio” [13, p. 1414]. Yet incubation space is no guarantee of an eventual breakthrough. Indeed, “innovations may remain stuck in these niches for a long time, when they face a mismatch with the existing regime and landscape” [13, p. 1414]. Within this space, ethanol remained protected throughout the 1980s and 1990s. However, important regulatory changes in the 1990s made the automobile socio-technical system a little more hospitable to this fuel.

Since 1970, under the Clean Air Act’s Mobile Source Program, the Environmental Protection Agency (EPA) has had the authority to regulate fuels and fuel additives. Additional regulations were added to the act in 1990 amendments, which mandated that oxygenates be added to gasoline to reduce smog in high pollution areas. This reformulated gasoline (called) was typically produced by mixing into gasoline either ethanol or methanol that has been processed into methyl tertiary butyl ether (MTBE). MTBE was initially the preferred oxygenate. Compared to ethanol, MTBE was cheaper to manufacture, has a higher energy content, is not water soluble, can be blended at the refinery and shipped through pipelines, and can be used in warm weather without increasing emissions [14].

A high-profile case involving groundwater contamination in California, however, quickly turned MTBE into a pariah additive. It was discovered that not only was MTBE leaking from ground storage tanks, but water contamination was also linked to motor vehicle and boat exhaust emission deposits [15]. By the late 1990s, various states had moved to ban MTBE outright, most notably California and New York. This move away from MTBE culminated with the Energy Policy Act of 2005, which repealed the Clean Air Act oxygenate requirement. In place of this requirement, the Energy Policy Act contains a provision that has been a boon for ethanol, namely, that annual production of gasoline must contain at least 7.5 billion gallons of "renewable fuel" by 2012. While the bill uses the term "renewable fuel," ethanol has been the largest benefactor of this provision given its prominence in the US renewable fuel market. The Energy Policy Act of 2005 not only created a level of market demand for ethanol that had previously never existed, but even more importantly, it signaled to potential investors the existence of *future demand*—specifically, of at least 7.5 billion gallons by 2012—which increased investor confidence in this still fledgling industry.

Research points to the role of expectations in technological change [16,17]. As Geels explains:

> Expectations can act as self-fulfilling prophecies, because they guide social actions in technological change [...] [by] indicating directions for R&D activities. This creates a 'protected space' for technology development actors, who receive resources to make the expectations come true. [18: 635, 636].

Given the Energy Policy Act of 2005, the 2007 State of the Union address, continued government support for corn producers (e.g., through the recently passed Farm Bill), and the domestic ethanol industry (e.g., through a $0.54 per gallon tax on all imported ethanol), it is obvious what the expectations are when it comes to biofuels in the US. Expectations point clearly to corn ethanol, and these signals, in guiding social action, investment, and research, are becoming self-fulfilling.

Yet even with all these regulatory openings, ethanol continues to encounter a mismatch with the existing regime, which explains the array of additional policies that shield the fuel from market forces. For example, between 1995 and 2005, the government provided approximately $164.7 billion in agricultural subsidies, of which $51.3 billion went to subsidize the production of corn [18]. The US General Accounting Office has estimated that over $19 billion in taxpayer support was given to the ethanol industry between 1980 and 2000. While less than that provided to fossil fuels and nuclear power in absolute terms, they exceed these subsidies when calculated in per unit energy terms [19]. The creation of market demand presupposes the ability to satisfy that demand. While the Energy Policy Act of 2005 provided signals to investors, industry, and the public about future demand, the ethanol industry still had to fulfill whatever immediate demand was created with its passing. The industry accomplished this because of decades-long incubation period created by the aforementioned subsidies. These subsidies gave ethanol space to establish new expert systems, ways of thinking, and institutional connections, all of which have contributed to the stabilization of an alternative technical artifact [7,20].

Additional incubating policies are discussed in later sections when considering other dimensions of the automobile socio-technical system. To speak more specifically to how these policies actually translated into broader socio-technical transitions, I now turn to another analytic dimension listed in Fig. 1, the expert system.

3. An expert system adjusting to biofuels

As the automobile socio-technical system grew during the early decades of the twentieth century, new forms of expertise were required to support associated technologies and solve problems that might arise through their use. Consequently, expert systems emerged in parallel with the emerging socio-technical system. For example, existing institutions like the YMCA (Young Men's Club of America), in collaboration with automobile clubs and firms, formed technical schools that supported the then-fledgling car network [21]. Expanding socio-technical systems can eventually lead to the creation of new academic sub-disciplines [22], which in the case of the (gasoline) automobile involved the emergence of, for example, automobile engineering, automotive machinery, and petroleum geology [8]. Over time expert systems can become self-sustaining [22]. They do this by taking on a structural quality, locking-in routines and "rules of thumb" among like-minded individuals that have become disciplined to see problems and solutions in certain ways (e.g., the problem of traffic congestion led to calls for more/wider roads, not less traffic) [8,23]. This creates a tendency among institutions and experts to frame issues in ways that reflect their expertise rather than in ways that could render obsolete the underlying socio-technical system (and by implication their status as an expert) [24]. Bijker refers to this closure around certain ways of doing and thinking as a "technological frame" [25]. Similar to a Kuhnian paradigm, a technological frame constrains and enables behaviors: "Within a technological frame not everything is possible anymore" [25, p. 192].

The aforementioned incubation space provided to ethanol during the 1980s and 1990s helped incubate alternative knowledge systems around biofuels. This eventually led to the creation of learning economies [26], where research in biofuels began experiencing increasing returns as expert systems slowly formed and solidified around ethanol. Before the recent boom, biofuels research was largely limited to a handful of Land Grant Universities (e.g., Iowa State University, Michigan State University, etc.). Today, however, we are beginning to witness the emergence of a self-sustaining expert system directed at biofuels, with dozens of universities becoming involved in this field of research. The formation of new disciplines (e.g., industrial biosystems engineering [27]), a refocusing of old ones (such as chemical and biomolecular engineering), and the creation of peer-reviewed journals (e.g., *Biotechnology for Biofuels*) are helping to stabilize and lock in a biofuel-oriented expert system. Organizational feet are beginning to form beneath these renewable fuels, which make the long-term stability of this expert system all the more likely.

There have also been incentives in recent years, from the standpoint of university administration, to bet on the ethanol juggernaut. Since the events of September 11, 2001, a steady stream of money, from both government and non-government sources is being directed toward biofuels. Baylor University, for example, was awarded a $492,000 grant by the U.S. Department of Agriculture (USDA) to assist in their research on cellulosic ethanol [28]. Other recent USDA grants for biofuels research include an $840,000 award to Washington State University for research into phenols in poplar trees (phenols have similar properties to petrochemicals), and a $50 million award to Michigan State University to further their research into ethanol [28]. In 2008, Iowa State University received a $944,000 grant from the US Department of Energy (DOE) to support a project that uses pyrolysis, gasification and nanotechnology-based catalyzation to produce ethanol [28]. Corporations themselves have begun to fund research into biofuels: British Petroleum, $500 million to a UC-Berkeley led consortium; Exxon Mobile, $100 million to Stanford University; Chevron, $25 million to UC-Davis; Conoco Phillips, $22.5 million to Iowa State University; Chevron, $12 million to Georgia Institute of Technology; Chevron, (amount not disclosed) to Texas A&M University [29]. Then there is the $369,000 donation from Wal-Mart to the Arkansas Biosciences Institute at Arkansas State University, which complemented a $1.48 million DOE grant to support cellulosic ethanol production research at that university [30].

To be clear, ethanol's success is not displacing conventional automobile expert networks, only causing them to shift to meet the demands of a post-breakthrough socio-technical system. The recent biofuel boom does not, for example, require an automobile mechanic with an entirely new skill set. Biofuel does not displace the internal combustion engine, which means it does not threaten, say, the discipline of automotive engineering, nor does it diminish the system's need for the automobile machinist or petroleum geologist. Yet ethanol's breakthrough does alter some of the "needs" that these experts are expected to address. For example, engineers must now deal with the need for fuel containing higher levels of ethanol (E85 blends) when designing engines and fuel distribution systems. Thus, while the post-breakthrough automobile socio-technical system now contains some new expert roles and network configurations, many others still look the same.

4. Production systems: increasing support for biofuels

The oil and automobile industries have a long history of challenging ethanol [31]. In recent years, however, this resistance has waned. As indicated by the industry-university biofuel partnerships, the oil industry has adjusted its research stream to include agro-fuels. In part, the petroleum industry's attitude shift reflects a diversification of R&D, where long-term economic sustainability (in a post-peak world) remains the goal. Likewise, the oil industry does not view the situation as win-lose. As Rick Zalesky, Vice President of Biofuels and Hydrogen at Chevron Technology Ventures, notes when discussing his company's position toward biofuels: "What helps a lot is that if I sell a gallon of ethanol today, it didn't mean I didn't sell gas. There's growth. It's a bigger pie" [29, p. 1201]. This position is reflected in a recent background report to Congress, which explains that "diluted blends of ethanol, such as E10, are considered to be 'extenders' of gasoline, as opposed to alternatives" [32, p. 8].

The automobile industry also has reasons to change its attitude toward ethanol. For example, the solution to the problems of high-priced/post-peak oil, global climate change, and energy dependence on non-democratic states is alternative *fuels*, not alternatives *to the automobile*. Put another way: the alternative to alternative fuels is unacceptable to this industry.

US automobile manufacturers have other reasons to support ethanol. Since 1975, the US government has required that automobile manufacturers meet the nation's CAFE (Corporate Average Fuel Economy) mileage standards or face penalties. With the passing of the Alternative Motor Fuels Act of 1988, car manufacturers received credits toward meeting the CAFE requirement when they produced flexfuel vehicles (FFVs)—automobiles capable of running on both gasoline and alternative fuels. From 1993 to 2004, manufacturers increased their CAFE by up to 1.2 mpg by producing these FFVs [33]. In other words, each FFV it produces helps manufacturers offset the higher-mileage autos they also produce. This offset strategy becomes particularly effective when FFVs are used in rental fleets, which helps inflate production numbers of these vehicles and in turn allows the manufacturer to produce a greater number of less-efficient automobiles [34]. Thus Szklo et al. note:

> The main reason why there are over six million flexfuel vehicles registered in the US has less to do with consumer-driven demand than with the long-established policy that credits these vehicles with artificially high fuel economy ratings. [33, p. 5418].

From a socio-technical standpoint, FFVs provide one solution to the "chicken-and-egg" problem associated with any shift toward an alternative fuel. These vehicles are said to offer a bridge between socio-technical systems, pre- and post-breakthrough [32]. The CAFE requirements, and the automobile manufacturers' use of those requirements to produce less-efficient vehicles, also helped shield FFVs from market forces (as mentioned, the demand for these autos was long an artifact of policy and not consumers). This created an incubation space that allowed manufacturers to essentially practice making alternative fuel vehicles. Importantly, however, this practice was limited by the engineering constraint that these vehicles still had to run on conventional gasoline. Thus, while providing a solution to the chicken-and-egg dilemma, FFVs ensure that both chicken and egg look similar to previous generations of chickens.

While FFVs indicate a degree of flexibility in the socio-technical system they equally demonstrate the system's resilience. The expanding presence of FFVs constrains the possibility of viable design solutions, as engineers and designers are forced to deal with the realities of making an engine that operates on *both* gasoline and ethanol. In time, this may lead to the emergence of rules of thumb, routines, and organizational networks that slowly lock-in design trajectories around *dual* (rather than *alternative*) fuel engines. In other words, the bridging function of FFVs, from pre-to post-breakthrough, may be more rhetoric than reality.

5. A changing cultural and symbolic landscape

The importance of cultural and symbolic resources in technological change has been well documented [25,35,36]. In the early years of the gasoline automobile, the electric and steam car came to symbolize femininity and old-fashionedness, respectively, which hindered their ability to win over popular imagination [37]. Similarly, as Pinch and Bijker describe, early bike design eventually stabilized around the form viewed as only for those of "means and nerve" [38]. While far from the entire story, part of ethanol's recent ascent can be attributed to its ability to resonate with the public and politicians. As the world's largest producer of ethanol, coupled with depressed corn prices in the years immediately following 9/11, the US was well positioned to capitalize on recent (largely positive) public sentiments toward renewable fuels.

The concept of "problem redefinition" [25, p. 278] speaks to the importance of framing problems, recognizing that how problems are perceived shapes what solutions are ultimately proposed and the socio-technical systems that eventually emerge. As Hughes explains, "technological systems [emerge to] solve problems or fulfill goals"[5, p. 53]. Ethanol proponents have a long history of emphasizing the non-renewable, non-domestic, polluting nature of oil [9]. While this discourse had some traction in the early decades of the twentieth century and again in the 1970s, recent shifts in the broader automobile socio-technical regime have helped to make this discourse transformative. For its part, the oil industry has become less fervent in its denial of these problems, as they now see a place for biofuels in the future [39]. This distinguishes the debate today from a century ago when the oil industry was firmly against alcohol fuel [2]. It is not, however, in the oil industry's interest to make the switch anytime soon away from gasoline. Perhaps this is why the oil industry is careful to talk about "renewable" or "bio" fuels and not *alternative* fuels (or alternatives *to* fuel).

Yet this positive symbolic capital could soon turn negative for ethanol. The "greenness" of ethanol is being challenged as studies report on, for instance, the emissions released during its production, manufacture, transport, and end-use consumption [40]. This could undercut claims that ethanol is a cleaner fuel that reduces pollution and helps combat global warming. Similarly, to protect the domestic ethanol industry, there is currently a 54¢ per gallon tariff on imported ethanol. If this tax was removed, Brazilian ethanol would most certainly begin to flow into the US given the lower production costs of Brazil's sugarcane ethanol [41]. Yet this would again make the US energy-dependent on another country and thus removes another powerful rhetorical device used by the ethanol industry, namely, that ethanol equals energy independence. Finally, rising global food prices challenge ethanol's status as a renewable fuel [42]. Whereas "renewable fuel" suggests a level of sustainability, rising food prices causes many to question the long-term implications that come with using this fuel.

I mention these challenges not to pick sides but to reveal a relatively recent shift in public sentiment toward ethanol, although it remains to be seen if this change in symbolic meaning will be transformative. There is an inevitable time lag between public opinion and meaningful change in other dimensions of the socio-technical system. The investments made in ethanol today are the result of sentiments held yesterday. Similarly, current policies and regulations reflect debates held months and in some cases years ago. While one can take back an opinion about a technological artifact, it is much more difficult to take back an ethanol plant, or 1000 newly manufactured FFVs, or a recently installed E85 pump. Past public sentiments are materializing around us with each passing moment.

6. Discussion

It is important to acknowledge how little ethanol disrupts certain dimensions of the conventional automobile socio-technical system. For example, biofuels "fit" with the existing road infrastructure (e.g., they still require roads and bridges); maintenance and distribution (e.g., they still require car dealerships and auto mechanics); and user practices and behavior dimensions (e.g., they still require consumers to go to gas stations to buy gas) of the automobile socio-technical system. This reflects the well-studied lock-in logic of socio-technical systems. As socio-technical regimes gain momentum [5], they become characterized by path dependence [22,43]. Is it any surprise, then, that the "alternative" fuel ultimately allowed into the system results in its transition and not in a total system upheaval and replacement? This begs the question: what lies ahead?

The lock-in tendencies of socio-technical regimes give some conceptual context to call for so-called second-generation biofuels, e.g., cellulosic ethanol, algae as a fuel source, etc. This logic reminds us that a shift to first-generation biofuels (e.g., corn ethanol) does not imply that further transitions will quickly follow. Indeed, if second-generation agro-fuels depart radically from the system's current ways of doing things, there is a good chance for future transitions will not happen at all. The transaction costs of such a transition may just be considered too great.

Future biofuel trajectories in part depend on the willingness of firms or the government to invest in alternatives to today's generation of biofuels. Most likely the government will have to play a major role in creating incubation space for future biofuels. Dominant firms seek to strengthen their position by re-investing in their core competencies, which creates a self-reinforcing, positive feedback loop that contributes to locking-in an existing socio-technical system (which in part explains why biofuels were "locked out" from the system for so long). Moreover, financial institutions prefer making loans to companies with collateral and an established market. This can rein-in socio-technical change as alternative trajectories become the interest of venture capital or government research programs [8].

A further locking-in tendency comes from an emerging global socio-technical regime. Initially, global practices surrounding novel technological artifacts are diffuse, leaving plenty of room for local improvisation. Over time, however, these practices become standardized, specific, and stable [44]. For centuries, alcohol fuel production and consumption were driven exclusively by local logics (e.g., local needs, available agricultural commodities, etc.). Recently, however, these local logics are being slowly replaced by global drivers. We are seeing the emergence of international biofuel alliances, such as between the US and Brazil, which encourage a sharing of ethanol-related technological know-how between countries [45]. Biofuel trade agreements, such as between Ecuador and the European Union, are also beginning to improve the global flow of these fuels [46]. Finally, biofuel pacts between OECD countries and non-OECD countries are being proposed that will institutionalize and harmonize the global trade of biofuels [41]. Taken together, these changing landscape conditions are helping to form a stabilizing (lock-in) global logic around a particular way of "doing" biofuel.

7. Conclusion

This paper sought to unpack the recent ethanol juggernaut by examining shifts within the various dimensions of the automobile socio-technical system. There are reasons why this transition occurred when it did. As Geels explains: "In the multi-level perspective there is no simple 'cause' or driver in transitions. For a transition to occur, dynamics at different levels should come together and reinforce each other" [13, p. 1414]. This is what happened in the case of ethanol. Today's biofuels boom is an artifact of transitions and reinforcing loops that have taken place for the last couple decades.

This paper also offers some cautionary words about the future. A recently published article on the costs and benefits of biofuels shows first-generation agro-fuels to be highly problematic in terms of their (negative) affects on global climate change, biodiversity, and food prices [47]. A shift to second-generation biofuels—where feed (such as field waste and perennials) is the raw input rather than food (e.g., corn)—is widely viewed as more sustainable than what the system currently produces [47,48]. Yet technological, institutional and social path dependency has been known to create barriers for innovation in bio-energy production [49]. Similar locking-out tendencies may hinder future transitions into second-generation biofuels. As of October 2008, 175 ethanol plants in the US had a total production capacity of 10.57 billion gallons [50]. Behind this refining infrastructure is a web of storage, transportation, and production networks designed specifically for corn ethanol. If future fuels have a poor fit within these current arraignments—that is, if they cannot utilize the sunken investments of first-generation biofuels—the transaction costs associated with their adoption might prove too great.

We must also not forget that future agro-fuels will require someone to grow them, which may require a change in farming patterns and behaviors. Farmers, too, can become locked in to specific commodity profiles as contracts, loans and capital investments limit management decisions [51]. Significant barriers will be encountered if future generations of biofuels require major capital reinvestments (e.g., in new farm machinery) and new producer skill sets to accompany these new production regimes.

These lock-in tendencies must be addressed by policy makers and politicians if future transitions are to occur, especially those requiring a radical departure from current socio-technical arrangements. In those instances, incentives, either from government or venture capital (given the aforementioned tendency among firms to reinvest in current arrangements), will be needed to reduce transaction costs associated with the research, development, and adoption of novel technological artifacts, although even here we find lock-in logics at work. Path-dependent tendencies, for example, have been shown to help shape the trajectory of government policy, specifically in the context of earmarks and subsidies [52]. The lock-in logics at all dimensions of the automobile socio-technical system must thus be addressed if radical transitions are to occur in the area of bio-energy in coming decades.

To be sure, paths can shift and take new directions. The current landscape conditions are such that it is impossible to predict with any accuracy the future trajectory of the socio-technical system in question, other than to say that conditions are so unsettled that a shift (the magnitude of which remains to be seen) could happen. In March 2009, the Obama administration put forth a number of policies linking energy more closely with environment and foreign policy (with global climate change now widely accepted, and energy, especially oil, independence).

In addition, new economic and market conditions, such as the near collapse of domestic automobile manufacturers, have created opportunities for massive investments in new—and in some cases green—technologies in an attempt to stimulate the economy. If such investments were partially directed at, for example, battery technology, which has improved considerably in recent years, all-electric cars could soon become technologically feasible. In light of the shift in mindset among people and politicians toward renewable fuels and energy independence, and the production of new jobs (many in the field of green technology) to hold back growing unemployment, an opening may present itself allowing transitions to occur. This is all, of course, speculative. Yet this is precisely the value of thinking in socio-technical terms, for it allows us to see technological change as complex and indeterminate.

References

[1] Renewable Fuels Association. Industry statistics. Available from: <http://www.ethanolrfa.org/industry/statistics/#A>; 2008 [accessed 18.09.08].
[2] Kovarik B. Henry Ford, Charles F. Kettering, and the fuel of the future. Automotive History Review 1998;32:7–27.
[3] Hebert HJ. Ethanol juggernaut moves through D.C. Available from: <http://www.usatoday.com/news/washington/2007-05-01-3741370429_x.htm>; May 1, 2007 [accessed 18.09.08].
[4] Geels F. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Research Policy 2004;33(6/7):897–920.
[5] Hughes T. The evolution of large technological systems. In: Bijker W, Hughes T, Pinch T, editors. The social constructions of technological systems. Cambridge, MA: MIT Press; 1987. p. 51–82.
[6] Hughes T. Networks of power: electrification in Western society, 1880–1930. Baltimore, MD: Johns Hopkins University Press; 1993.

[7] Rip A, Kemp R. Technological change. In: Rayner S, Malone EL, editors. Human choice and climate change, vol. 2. Columbus, OH: Battelle Press; 1998. p. 327–99.
[8] Unruh G. Understanding carbon lock in. Energy Policy 2000;28:817–30.
[9] Berton H, Kovarik W, Sklar K. The forbidden fuel: power alcohol in the Twentieth Century. New York: Boyd Griffin; 1982.
[10] Carolan M. Ethanol versus gasoline: the contestation and closure of a socio-technical system in the USA. Social Studies of Science 2009;39(3):421–48.
[11] Hahn R, Cecot C. The benefits and costs of ethanol. Working Paper #07-17. Washington, DC: AEI Center for Regulatory and Market Studies; 2008.
[12] Kemp R, Schot J, Hoogma R. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technological Analysis and Strategic Management 1998;10:175–96.
[13] Geels F. Analysing the breakthrough of rock 'n' roll (1930–1970): multi-regime interaction and reconfiguration in the multi-level perspective. Technological Forecasting and Social Change 2007;74:1411–31.
[14] Reitze A. Should the Clean Air Act be used to turn petroleum addicts into alcoholics? Environmental Forum; 2007 (July/August):50–60.
[15] Williams P. MTBE in California drinking water: an analysis of patterns and trends. Environmental Forensics 2001;2(1):75–85.
[16] Van Lente H, Rip A. Expectations in technological developments: an example of prospective structures to be filled in by agency. In: Disco C, van der Meulen BJR, editors. Getting new technologies together. Berlin and New York: Walter de Gruyter Publishing; 1998. p. 195–220.
[17] Brown N, Michael M. The sociology of expectations: retrospecting prospects and prospecting retrospects. Technology Analysis & Strategic Management 2003;15(1):3–18.
[18] Philpott T. The short-term solution that stuck: where farm subsidies came from and why they're still here. Grist. Available from: <http://www.grist.org/comments/food/2007/01/30/farm_bill2/>; January 30, 2007 [accessed 13.12.07].
[19] General Accounting Office. Tax incentives for petroleum and ethanol fuels. GAO/RCED-00–301R. Available from: <http://www.gao.gov/new.items/rc00301r.pdf>; 2000 [accessed 29.06.08].
[20] Geels F. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Research Policy 2004;33(6–7):897–920.
[21] Fink J. America adopts the automobile age. Cambridge, MA: MIT Press; 1970.
[22] Nelson R, Winter S. An evolutionary theory of economic change. Cambridge, MA: Harvard University Press; 1982.
[23] Nelson R. Recent evolutionary theorizing about economic change. Journal of Economic Literature 1995;33:48–90.
[24] Christensen C. Innovation and the general manager. Homewood, IL: Irwin; 1999.
[25] Bijker W. Of bicycles, bakelites, and bulbs: toward a theory of socio-technical change. Cambridge, MA: MIT Press; 1995.
[26] Agrote L, Epple D. Learning curves in manufacturing. Science 1990;247:920–4.
[27] Chen S. Industrial biosystems engineering and biorefinery systems. Chinese Journal of Biotechnology 2008;24(6):940–5.
[28] Biofuels Digest. USDA awards $492,000 to Baylor to study cellulosic ethanol inhibitors. Available from: <http://www.biofuelsdigest.com/blog2/2008/05/23/usda-awards-492000-to-baylor-to-study-cellulosic-ethanol-inhibitors/>; May 23, 2008 [accessed 22.09.08].
[29] Sheridan C. Big oil's biomass play. Nature Biotechnology 2007;25(11):1201–3.
[30] Christiansen R. Wal-Mart donates $369,000 for ethanol research. Ethanol Producer website. Available at: <http://www.ethanolproducer.com/article-print.jsp?article_id=4777>; October 2008 [accessed 22.09.08].
[31] Giebelhaus A. Resistance to long-term energy transition: the case of power alcohol in the 1930s. In: Perelman L, Giebelhaus A, Yokell M, editors. Energy transitions: long-term perspectives. Boulder, CO: Westview Press; 1979. p. 35–63.
[32] Yacobucci B. Fuel ethanol: background and public policy issues. Washington, DC: Congressional Research Service. Available from: <http://fpc.state.gov/documents/organization/62837.pdf>; January 24, 2007 [accessed 04.03.08].
[33] Szklo A, Schaeffer R, Delgado F. Can one say ethanol is a real threat to gasoline? Energy Policy 2007;35:5411–21.
[34] Ries R. Flex fuel for Ag? Farm Industry News. Available from: <http://www.farmindustrynews.com/mag/farming_flex_fuel_ag/index.html>; September 1, 2006 [accessed 31.03.08].
[35] Kline R, Pinch T. Users as agents of technological change: the social construction of the automobile in the rural United States. Technology and Culture 1996;37(4):763–95.
[36] Pinch T. The social construction of technology: a review. In: Fox R, editor. Technological change: methods and themes in the history of technology. Netherlands: Harwood; 1996. p. 17–36.
[37] Jamison A. The steam-powered automobile: an answer to air pollution. Bloomington: Indiana University Press; 1970.
[38] Pinch T, Bijker W. The social construction of facts and artifacts, or how the sociology of science and the sociology of technology might benefit from each other. Social Studies of Science 1984;14:399–441.
[39] Caesar W, Riese J, Seitz T. Betting on biofuels. McKinsey Quarterly 2007;2:53–63.
[40] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and biofuel carbon debt. Science 2008;319:1235–7.
[41] Mathews J. Biofuels: what a biopact between North and South could achieve. Energy Policy 2007;35:3550–70.
[42] Runge C, Senauer B. How biofuels could starve the poor. Foreign Affairs 2007;86(3):41–54.
[43] Geels F. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–30). Technology Analysis & Strategic Management 2005;17(4):445–76.
[44] Deuten J. Cosmopolitanising technology: a study of four emerging technological regimes. Enschede, Netherlands: Twente University Press; 2003.
[45] The White House. President Bush and President Lula of Brazil discuss biofuel technology. Press Release, Office of the Press Secretary. Available from: <http://www.whitehouse.gov/news/releases/2007/03/20070309-4.html>; March 9, 2007 [accessed 13.12.07].
[46] Seelke C, Yacobucci B. Ethanol and other biofuels: potential for US-Brazil energy cooperation. Washington, DC: Congressional Research Service. Available from: <http://www.wilsoncenter.org/news/docs/CRS%20Report%20on%20US-Brazil%20potential%20cooperation%20on%20biofuels.pdf>; September 27, 2007 [accessed 31.03.08].
[47] Carolan M. The costs and benefits of biofuels: a review of recent peer-reviewed research and a sociological look ahead. Environmental Practice 2009;11:17–24.
[48] Pahl G. Biodiesel: growing a new energy economy. White River Junction, VT: Chelsea GreenPublishing; 2008.
[49] Van der Laak W, Raven P, Verbong G. Strategic niche management for biofuels: analysing past experiments for developing new biofuel policies. Energy Policy 2007;35:3213–25.
[50] Schill R. US ethanol production. Available from: <http://www.ethanolproducer.com/article.jsp?article_id=4735>; October 2008 [accessed 25.09.08].
[51] Sherrington C, Bartley J, Moran D. Farm-level constraints on the domestic supply of perennial energy crops in the UK. Energy Policy 2008;36:2504–12.
[52] Law M, Tonon J, Miller G. Earmarked: the political economy of agricultural research appropriations. Review of Agricultural Economics 2008;30(2):194–213.

Michael S. Carolan is an Associate Professor of Sociology at Colorado State University. He is currently engaged in three streams of research. One involves the examination of biofuels through the conceptual and analytic frameworks provided by sociology of technology. The second focuses on patent law, specifically as it applies to biotechnology. Utilizing concepts from the field of Science and Technology Studies, this line of research highlights the work that goes into giving biotechnological artifacts their objective qualities. He is also interested in the relationships between innovation, patents, and development. His third stream of research, grounded in the theoretical framework known as embodied realism, details how changing relationships to food and agriculture have changed our understanding of these phenomena.