

Retooling: A Model of Sociotechnical Change for Turbulent Times

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Abstract

Retooling is a ubiquitous practice that mobilizes innovation, maintenance, and repair to address sociotechnical change in times when transformations seem difficult to accomplish. Retooling entails an *intentional reorientation* of purpose, foregrounds the *nonlinear trajectories* of technological and scientific shifts, and focuses our attention on the *meso* level of organizational and collective life. This paper offers a theorization of retooling grounded in two case studies: one about water reuse technologies in the United States and the other about efforts to refashion the sugarcane industry in Brazil. We suggest that retooling is a useful analytic tool at a time when both innovation and maintenance seem not only difficult to differentiate but also insufficient for explaining sociotechnical change on their own. Furthermore, during turbulent times when change seems difficult to accomplish, retooling offers a capacious conceptualization that highlights the political orientations that inspire all sociotechnical transformations and the possibilities that emerge from mobilizing what-is to bring about what-should-be.

Keywords

water; maintenance; repair; innovation; infrastructure; sociotechnical change; retooling

Introduction

Efforts to extract value from previously discarded or undervalued technologies have increased in recent years. This shift, often initiated in response to economic, political, and environmental turmoil, is a type of sociotechnical change that does not fit neatly into inherited categories of maintenance and innovation. For example, in the United States, direct potable water reuse—a method of transforming wastewater into drinking water with a long technological history—is re-emerging as a prominent component of political visions for sustainable economic growth. In Brazil, a late-twentieth-century focus on developing the

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sugarcane industry to produce refined sugar and biofuels is refashioned to manage agricultural waste as a solution to climate change. In both cases, sociotechnical change occurs through what we call *retooling*: a ubiquitous sociotechnical practice where actors intentionally mobilize the old and the new to fulfill political desires at times when change seems difficult to accomplish.

Rather than explaining change, or lack thereof, in terms of innovation or maintenance, retooling openly and purposefully centers both at once. People and organizations retool the technologies around them to respond to critical and (techno)utopian calls for innovation to address existential threats (e.g., [Dickel and Schrape 2017](#)). Retooling allows people to embrace maintenance and repair, building hope in the context of intensified inequality, destabilized institutions, and populist remakings of the status quo. In this essay, we develop the concept of retooling as a way to answer the following questions: How do people embrace innovation without further fetishizing the new? And how do people use what already exists to intervene in the immediate present and bring the future to what it should be?

Retooling offers provocative perspectives on these questions, illuminating efforts to enact sociotechnical change *for* and *in* times of uncertainty. When actors retool technologies, ideas, or values, they intentionally combine the novel with the already existing to respond to shifting political conditions and articulate visions of the future. It is in this tactical redirection of science and technology toward envisioned futures that retooling differs from other forms of reuse or repurposing. For example, when governments and businesses imagine an electricity future decoupled from large-scale grids by using home battery systems, microgrids, and generators, those who embrace such changes not only further a vision of development in underserved areas, they also propel a libertarian ideology of escaping state control in the era of techno-oligarchy ([Nucho 2022, 268](#)). They retool technologies for a variety of distinct political purposes, presenting them as new versions of what was there before. In our conceptualization, retooling offers a language of change that speaks to localized, meso-level dynamics that are particularly intensified in our current conjuncture.

Questions around the old and the new have resulted in intense and productive debates around the form of innovation, on the one hand, and that of maintenance and repair, on the other. Scholars contributing to these conversations have repeatedly dismantled the apparent dichotomy between change and stasis ([Vinsel and Russell 2020](#)). And yet, despite their careful work, a certain path dependency remains, turning innovation into a celebration of the new at the expense of what remains from the past, and maintenance into something that emphasizes the careful preservation of what is in order to deflate the hype of the new. We suggest that retooling can help sidestep the persistent binaries that frame change and stasis as opposites, despite scholars' best efforts to critique and transcend those binaries. As a tactic, we situate retooling within a family of strategies for change that scholars have documented extensively, such as prototyping ([Corsín Jiménez 2014](#)), repurposing ([Lepawsky 2018](#)), and experimentation ([Lezaun et al. in Felt et al. 2017, 195–221](#)), all of which bring together that which could be with that which is.

To make these arguments, our essay begins by situating retooling in relation to STS scholarship on sociotechnical change, placing discussions around innovation and maintenance in their broader context. We draw on STS scholarship rooted in the Global South and on feminist interventions to highlight how relations between the old and the new are situated within asymmetric power relations along various axes. Following that contextualization, we describe three analytic affordances of retooling as a concept: intentional reorientation of purpose, nonlinear trajectories, and interventions at the meso level. The research article

then moves to two brief case studies of retooling—the first focused on direct potable water reuse in the Western United States, the second on sugarcane-based biofuel production in Brazil. We conclude with reflections on how the concept of retooling could aid in understanding sociotechnical change and its politics in an era of intensified, uncertain, even dystopian transformation. We hope that retooling can serve as another conceptual tool to continue eroding the persistent dichotomy between innovation and maintenance in public discourse, as well as the unintentional reproduction of that dichotomy in scholarly works.

Sociotechnical Change and Retooling

STS scholarship demonstrates the contextual specificity of sociotechnical change—that is, how the effects of any given technological artifact or sociotechnical system are always determined by the broader social system in which it exists. By demonstrating the contingency of sociotechnical change, this scholarship challenges the idea that technologies follow inherent trajectories that are independent of social, political, and economic conditions (e.g., [Smith and Marx 1994](#); [Bijker and Law 1992](#)). Since the 1970s, STS scholars have developed a range of theoretical frameworks to this end, articulating the co-constitution of social and technological change often through empirical examples, from bicycles to electrical networks to washing machines ([Bijker 1997](#); [Law and Callon in Bijker and Law 1992, 21–52](#); [Hakken 1993](#); [Geels 2007](#); [Parr 1997](#)). As a result, it is a well-established STS insight that, despite the apparent stability of sociotechnical systems, it is historical specificity and sociality that make one sociotechnical system persist rather than another.

Feminist STS scholars transformed this literature by insisting on how the emphasis on stabilization and persistence in the wake of scientific and technical disruption and controversy glossed over the struggles and negotiations necessary for that apparent stability to hold. These scholars have demonstrated how an emphasis on local contingencies and emergent agents can unwittingly obscure larger and enduring power structures. They powerfully highlighted how both change and continuity are ultimately forms of struggle. They showed how even the change that supposedly represented progress was made possible by power asymmetries that cemented existing male-female hierarchies ([Harding 2011](#)), perpetuated racial and gender-based forms of dispossession ([Cowan 1983](#)), and maintained dichotomies between natural/artificial ([Suchman 2007](#)), nature/culture ([Haraway 1988](#)), and advanced/developing countries ([Philip 2004](#)). Most recently, feminist scholars have continued the work of demonstrating how technological stabilization is linked to imperialism, transnational capital, and military programs ([Pardo Pedraza 2020](#); [Murphy 2017](#); [Foster 2017](#); [Suchman 2007](#); [Ballestero 2023a](#)). In these ways, feminist work helped shift the focus of STS scholars from localized processes of sociotechnical disruption or stabilization—the subject of much of the early STS work of the 1970s and 1980s—to the role of inequalities in ongoing sociotechnical change at multiple scales.

In a parallel vein, scholars interested in non-Euro-American histories challenged diffusionist models of sociotechnical change based on the idea of technological propagation from global centers of power— notions rooted in colonial assumptions ([Ballestero 2023b](#); [Anderson 2002](#); [Pollock 2019](#); [Soto Laveaga 2020](#)). For example, development literature from Euro-American scholars often posited that sociotechnical change in Latin America, Africa, and Asia happened primarily through the importation of science and technology from abroad, and that without such importation societies would stagnate ([Geertz \[1963\] 1969](#); [Escobar 1995](#); [Mavhunga 2017](#)). Such claims reflect evolutionary and racist classifications that render some people and regions as lagging and others at the forefront of sociotechnical change ([Suarez-](#)

[Días, García-Deister, and Vasquez 2017](#); [Kowal et al. 2013](#); [Subramaniam 2014](#)), obscuring the histories of technological innovation coming from indigenous worlds before and through colonization ([Kolopenuk 2020](#); [TallBear 2013](#); [Liboiron 2021](#); [Ballestero et al. 2024](#); [Barrera-Osorio 2009](#); [Premo 2017](#)). Furthermore, as Eden Medina et al. (2014) argue, such portrayals ignore the changes that occur as technologies are reterritorialized in different cultural and geographic contexts (see also [Kreimer and Vessuri 2018](#)). Similarly, in his examination of African technology as a way of doing rather than as a thing, Clapperton Chakanetsa Mavhunga (2014) inverts the designer-user dichotomy that defines much of the scholarship on technology adoption and diffusion (c.f. [Rogers \[1995\] 2003](#)), focusing on how “everyday innovation” imbues the values, interests, and practices of users in the very essence of technology.

Recently, discussions about sociotechnical change have largely been refracted through the figures of innovation and maintenance, not the least because of the prominence of these concepts as vernaculars of technological speech ([Suchman and Bishop 2000](#); [Stilgoe and Guston in Felt et al. 2017, 853–880](#); [Godin 2017](#)). The term “innovation” is commonly used to describe how novel technologies are conceived, adopted, and disseminated in commercial practices ([Godin 2008, 2017](#); [Berkhout 2006](#)). Since the mid-twentieth century, public discussions about innovation have also reflected a utopian faith in the capacity of technology to create new futures by both feeding capitalist value accumulation and promising to solve urgent problems, from poverty to climate change ([Borup et al. 2006](#); [Guthman and Biltekoff 2021](#); [Keeler et al. 2019](#); [Garduño García and Gaziulusoy 2021](#)). This technocentric solutionism is part of a long history of cornucopianism ([Jonsson 2014](#); [Jonsson and Wennerlind 2023](#)), which envisions technological innovation as enabling new kinds of world-making that correct or add what is missing from existing worlds. In this sense, innovation feeds the future-oriented desires for change that circulate among different publics, including policymakers, venture capitalists, funders, and everyday citizens ([Brown and Michael 2003](#); [Konrad et al. in Felt et al. 2017, 465–493](#); [Tutton 2011](#)).

In this kind of innovation talk, the new is distinguished by its distinct ethical and analytical commitments and by the involvement of new sets of actors. Yet, as Suchman (2011) notes, innovation is defined less by “a property [of newness] than by calling out differences from whatever is referenced as the thing that came before” ([ibid., 15](#)). In this scenario, “real” innovation is viewed as lying beyond the scope of low-tech, low-capital interventions and those lacking specialized technical training ([Parthasarathy 2022](#)). To account for the kinds of newness that nonetheless emerge under such conditions, the concept of innovation is modified through qualifiers such as “frugal” or “grassroots” to signal efforts that serve overlooked markets through cost-reduction, core functionality, and performance optimization ([Weyrauch and Herstatt 2017](#)). These kinds of qualified innovations aim to address local needs through “minor, incremental adjustments or imitations that bridge a technological gap,” in order to bring about solutions that are out of reach due to economic or geopolitical conditions ([Kumar and Sharma 2024, 2](#)). In other words, in its broader sense, innovation is to be found everywhere, from sites focused on “emerging technologies” to those seeking its democratization as a universal social good.

STS scholars have proposed maintenance as an alternative approach to understanding technological change and continuity. In part a response to the emphasis on the new in governmental policies and the popular imagination, as well as in certain strands of STS scholarship, maintenance seeks to bring light to the undervalued labor of keeping scientific practice, technologies, and infrastructures running ([Russell and Vinsel 2018](#); [Denis et al. 2023](#)). Scholars in this area have argued that maintenance, including

care and repair, plays a critical role in the successful operation and long-term persistence of infrastructure and technology ([Jackson 2014](#); [Graham and Thrift 2007](#); [Barnes 2017](#); [Pollock and Williams 2010](#); [Henke 2008](#)). Conceptualizations of maintenance as upkeep ([Denis et al. 2015](#)), technology-in-use ([Edgerton \[2007\] 2011](#)), and repair, reuse, and repurposing (e.g., [Jackson 2014](#); [Mattern 2018](#)) have enabled scholars to closely analyze how maintaining technology use over time, along with its social and cultural implications, requires creativity and invention. Such practices can give objects multiple lives ([Lepawsky 2018](#)) and upend narratives of linearity ([Gregson et al. 2010](#); [Liboiron and Lepawsky 2022](#)). Given its essential role in keeping societies functioning, maintenance can also become a site for co-optation or even oppression, imposing forms of radical, racialized, and gendered care as a mode of survival (c.f. [Hobart and Kneese 2020](#); [Mattern 2018](#); [Rodríguez et al. 2024](#)). By focusing on maintenance as a set of practices that are inherently networked and involve many actors, this scholarship helps correct, to some extent, a historic overemphasis on a group of actors (often white or male) in STS scholarship.

As many of these scholars note (e.g., [Russell and Vinsel 2018](#)), any stark opposition between innovation and maintenance is a false dichotomy. Maintenance itself demands creativity, flexibility, and, indeed, innovation. At the same time, many things labeled as innovations are “artful integrations” ([Suchman 2002](#)) or continuations of existing practices, even as they mobilize utopian imaginaries in which innovation provides a way out of intractable problems ([Sadowski and Bendor 2019](#)). Despite these scholarly nuances, public debate on technological and scientific change continues to figure innovation as the primary source of hope for a new and better future. In this telling, maintenance becomes valuable only inasmuch as it, too, is innovative or enables innovation. These intricacies can have the unintended or even ironic effect of reactivating the binary between innovation and maintenance that scholars have worked so hard to dismantle. We offer retooling as a way to sidestep this legacy.

Retrofitting: Three Analytic Affordances

Building on the scholarly insights highlighted above, and attending to the recalcitrance of the contrast between the old and the new in understandings of innovation and maintenance, we ask: Might there be a more direct way of conceptualizing the pace, qualities, and modalities of a kind of sociotechnical change that is about the old and the new at once? Is there a way to recognize those imbrications while keeping in sight the broader political values and visions for the future that inspire both the maintenance of specific components of what is and the transformation of others into something new?

We propose retooling as a concept well-suited to addressing these questions. Retooling attends to how people mix, in varying proportions, the old and the new to address the broader material and political contexts in which they operate. Retooling is thus a kind of sociotechnical change that is organized explicitly around specific political programs. That is, it responds to demands and expectations about how to organize collective life, enabling stakeholders to “do something” so that systems and infrastructures can achieve certain goals and advance certain interests while foreclosing others.

Retrofitting thus brings into relief the pivoting, reorienting, or tweaking of already existing science and technology. We use these three related but slightly different terms to highlight subtle aspects of retooling. Retooling emphasizes political and economic concerns that emerge when actors mobilize technology and technology-speak to pivot towards new, or newly reframed, collective objectives required by larger geopolitical, economic, environmental, and historical shifts. Like the tweaking of a coat for a better

fit or style, retooling is an intentionally reflexive, tactical act that responds purposefully to the worlds we live in. In sum, retooling explicitly connects technical questions to the politics of acting, relating what *is* to what *could* be.

In STS scholarship, retooling has a history, albeit a limited one. The concept has been deployed to account for sociotechnical change in higher education, technoscientific subjectivities, and finance. Rosalind Williams describes ideologies of engineering education at MIT as an illustration of how “a larger society devoted to technological innovation” ignores how engineers “retool” society by adapting to their surroundings (2002, 13); here, retooling is offered as an alternative to innovation talk. Wenda Bauchspies and Maria Puig de la Bellacasa use retooling to “carefully but intentionally [. . .] emphasize the re-making of a usable tool” while also recognizing that such a tool “often has a life of its own” (2009, 227–28); here retooling highlights the agency of different subjects and subjectivities in defining the value of an instrument. Finally, in the area of financial technologies, Annelise Riles (2013) notes how regulators retool insights from anthropology and sociology to build new approaches to regulation in the wake of the 2008 financial crisis; in Riles’ hands, retooling describes the reorientation of practices such as “peer review” and “naming and shaming” through transplantation into a new sector.

Building on these insights and attending to our contemporary context, we propose a notion of retooling that is imbued with three key analytic affordances. First, retooling entails an *intentional reorientation* of purpose. Complementing STS work that uncovers how new technologies and scientific findings frequently stem from unexpected results or unplanned research findings (Rheinberger 1998; Jansen 1995; Lomnitz and Cházaro 1999), retooling privileges something else: intentional reorientation. Such intentions take already existing technologies and reorient them tactically to fit new conditions or political demands. At the same time, while retooling can unfold within the context of planning and other kinds of programmatic orientations towards action, it is distinct from such forms of modernist means–end articulations precisely because it troubles the means–end distinction. In the context of retooling, means can transform ends, and vice versa. Thus, retooling involves shifting away from goals that are no longer desirable or feasible and repurposing existing knowledge or technologies in the service of newly adopted goals. For example, one might think of how grassroots oppositional movements retool techniques and materials from industry and the state, which are then appropriated and reintegrated into apparatuses of state surveillance and surveillance capitalism, against which new oppositional visions of future change are then articulated, which again entail the repurposing of old technologies, and so on (e.g., Shapiro, Zakariya, and Roberts 2017).

Second, retooling foregrounds the *nonlinear trajectories* of technological and scientific change without reproducing the success/failure dichotomy or privileging the unexpected. While understandings of nonlinear technoscientific change abound (Godin 2006; Rosenberg 1994; Dagnino and Velho 1998; Calvert 2006), these often use nonlinearity to highlight setbacks, so-called failures, unintended consequences, or the deferral of success via ideas of potentiality (Kneas 2016). In contrast, retooling focuses on offshoots and pivots, taking them as central components of everyday technoscientific practice. Retooling centers on the constant metamorphosis of knowledge and technology in response to different contextual and historical pressures. These transformations can turn successes into failures, failures into successes, and seemingly irrelevant developments into critical resources as conditions shift. Retooling focuses on these tactical redirections of science and technology, showing how people can make the same technologies leap from one

area of social life to another, from one political valence to another, or from one set of ethical concerns to another. This technoscientific nonlinearity can also be a form of political nonlinearity, shifting the purpose and ethical implications of particular technologies from constructive to destructive constellations.

Third, retooling brings our attention to the *meso level* of organizations, institutions, and political programs in the form of policies, initiatives, and even best practices that become widespread, adjusting everyday life.¹ Tracing these reorientations requires careful attention to institutions that lie between the local and the global, the micro and the macro. Retooling is of little use for understanding individuals or individual action in isolation, just as it is poorly suited to the analysis of extensive conditions or regimes that span a wide range of highly differentiated contexts, political visions, and technological systems. Instead, retooling offers the most powerful insights when it is based on careful empirical work on situated cases that connect different geographic sites and time periods through the reorientations and pivots that make distributed actions fit under a shared vision. Put differently, the study of retooling weaves together geographically distributed, intermittent, and historically separated events at the meso level to show how they crystallize technological change across discontinuous temporalities and distributed geographies.

In sum, retooling encompasses both continuity and change, holding maintenance and innovation together. It refuses two problematic assumptions about how change unfolds: on the one hand, the notion that the world can be changed without attending to structures and histories in place, as if transformation were merely a matter of accepting new ideas. And on the other hand, the idea that the world cannot be changed at all because of path dependency and reproductive forces that make transformation impossible to accomplish. It is important to note, however, that retooling is not necessarily utopian or dystopian; nor does it offer a guarantee of more equitable futures. Nevertheless, retooling helps us track how changes can come into being.

In the next section, we present two cases that illustrate our conceptualization of retooling. One concerns the changing value of wastewater in areas of the United States; the other concerns efforts to refashion the sugarcane industry in Brazil to meet emerging economic and environmental challenges. Whereas in the first case, ideas and laws are retooled, in the second, technologies used in production processes are. In both cases, retooling helps reveal the complex relations between the old and the new as political challenges demand new articulations of technoscience.

Case 1: Direct Potable Reuse: From Abject to Accepted

In this case, based on research conducted by Christy Spackman we examine direct potable reuse (DPR) as a site of retooling public conceptions and legal structures in the United States to define quality water not by its origins but by its end characteristics. We focus on Clean Water Services (CWS), an Oregon utility in the Portland region that began to transform its wastewater treatment practices in the early 2000s, situating the utility's advocacy of DPR within the longer history of the technique. Potable reuse refers to a suite of activities that treat wastewater so that it can be returned to the distribution system, either via an

¹For a parallel argument about the need for meso-scale analysis, specifically within the history of science, see [Güttler 2019](#).



environmental buffer (i.e., indirect potable reuse) or directly ([Keller et al. 2021](#); [Scruggs et al. 2020](#)). Recently, wastewater has re-emerged as a “new” resource stream, reconnecting the present moment with past practices of valuing wastewater ([Tarr 1979](#)). Guest et al. ([2009](#)) describe this as a shift from “wastewater to resourcewater” (see also [Qu et al. 2019](#)). Under this model, effluent is split into streams that are then treated to release energy and recover valuable components such as metals, nutrients, biogas, and—especially critical for arid regions—water (e.g. [Barros et al. 2019](#)).

In the U.S., DPR’s advocates seek to combine wastewater treatment approaches mandated by the Clean Water Act of 1972 with advanced water treatment technologies. By current standards, advanced treatment technologies successfully remove physical, chemical, and biological contaminants, producing water that can be directly returned to the municipal water supply after remineralization. By reorienting already-existing technologies towards cleaning wastewater for reuse, engineers and others offer to address a range of political concerns, including the need for new revenue streams to facilitate rebuilding failing water infrastructure ([Greer 2020](#)), the need to align with new regulations governing wastewater discharge, and the desire to minimize water usage restrictions despite scarcity. For DPR’s advocates, framing wastewater as a resource for extraction of metals, minerals, and water, appears as the logical (and possibly inevitable) next step in the care, treatment, and delivery of water.

Despite research demonstrating DPR’s safety, it remains socially contested and legislatively restricted ([Ormerod and Scott 2013](#)). A multi-sited, multi-temporal effort at the meso level to retool public notions of what makes quality water has loosened those constraints. Advocates’ efforts to make provisioning systems, regulations, and public perceptions of those systems and their safety amenable to DPR depend on a retooling of the social understandings and legal structures that undergird contemporary definitions of water quality. The retooling of definitions of water quality (which I focus on here) reflects larger efforts to integrate historically separate paths for managing drinking water and wastewater.

Engineers first proposed piloting DPR as a potential response to drought in 1970 in Denver, CO ([Work et al. 1980](#); see also [Olivieri et al. 2020](#)). In 1980, the U.S. Environmental Protection Agency (EPA) convened a group of experts to review the technology. Presenters at the EPA workshop recommended developing new standards that redefined potability; instead of “attempting to define a potable water by defining its source of supply,” they suggested undoing early twentieth-century regulations (and cultural practices) that divided drinking water and wastewater streams ([U.S. EPA 1982, 15](#)). The experts’ recommendations posited that if the water produced was clean and safe, its source did not matter ([Cotruvo 2016](#); [U.S. EPA 1982](#)). The proposal aimed to intentionally reorient engineers’, city planners’, regulators’, and policymakers’ attention. Instead of defining quality by how biologically or chemically contaminated a source water was, the proposal collapsed the distinction between wastewater and drinking water by defining quality as dependent on the technological and scientific capacity to remove contaminants.

Contemporary proponents of unifying water and wastewater call this the “One Water” approach. One Water centers the idea that “all water, regardless of its source, has value” ([Tuser 2021](#)). It draws together concerns over water scarcity with the idea that wastewater is an underutilized resource. In the past, and in other locales, wastewater served as a valuable resource for fertilizer production ([Gandy 1999, 30](#); [Ferguson 2014](#); [Tarr 1979](#)). However, as water-based sanitation practices emerged in the late nineteenth and early twentieth centuries in the U.S., Europe, and elsewhere, wastewater became socially suspect ([Goubert 1986](#); [Melosi \[2000\] 2008](#)). One Water seeks to overcome these historical divisions.

Experts' arguments that people should judge water by its final quality rather than its source have historically stumbled, however, in the face of many people's visceral "yuck" response ([Smith et al. 2018](#); [Tennyson et al. 2015](#); [Alley and Alley 2022](#)). Surveys conducted by water researchers from the 1970s to the early 2000s demonstrated that while people accepted using recycled water for distant practices like watering golf courses, acceptance decreased as use became more intimate, such as with swimming or drinking ([Bruvold 1985](#); [Hartley 2006](#)). Starting around 2014, DPR proponents began redirecting their public engagement approach from trying to educate away concerns to using approaches that seek to viscerally convince stakeholders to adopt a One Water perspective through opportunities to taste, touch, smell, and see the water ([Manheim 2024](#)). This tactical redirection leaps from one arena of social life to another: whereas earlier education efforts centered on pamphlets, posters, and outreach meetings, with their assumptions of behavior based in rational choice (e.g., [Bruvold 1985](#); [Tennyson et al. 2015](#)), recent efforts increasingly incorporate a modified form of taste education that uses public tastings to activate positive reactions and shift conceptions of what makes quality water ([Manheim and Spackman 2022](#); [Spackman 2024](#)).

Craft beer brewing may be the most charismatic of the techniques mobilized by DPR's proponents to retool social and legislative attachments to existing conceptions of quality water. Retooling public conceptions of wastewater's potential as a resource through beer brewing took a nonlinear path. In 1993, the Los Angeles Sanitation District proposed building a pipe to transport reclaimed water to the Irwindale area for filtration into the aquifer. This proposal resulted in vehement opposition from Miller Brewing Co., whose Irwindale plant drew its water from the aquifer. Miller took out a full-page advertisement in the Thursday, September 8, issue of the *Los Angeles Times* emphasizing that they never used reclaimed water, while also using public comment periods and legal action to delay the plan's approval ([Sklar 2015](#); [Clifford 1994](#); [Los Angeles Times 1994](#)). It was in this context that Miller's public relations specialist reportedly coined the phrase "toilet-to-tap" ([Sklar 2015](#)), a linguistic shortcut still mobilized today by opponents in the debate over whether one should "evaluate a water on its quality, not its history" ([Livingston 2020](#)). It took another twenty years, and a different geographic location, before beer would again be explicitly linked with potable reuse, but this time under a positive framework.

It was folks working with Clean Water Services who first suggested brewing beer with DPR water in 2013. To understand why a region in Oregon with significant rainfall would become a locus for new engagement strategies, we need to rewind to the 1970s. The utility discharges into the slow-flowing Tualatin river. At multiple points during the 1970s and 1980s, agricultural run-off, over-use, deforestation, and wastewater discharge led to the Oregon Department of Environmental Quality listing the Tualatin as "water-quality limited" ([Faha 1999](#)). Like all US wastewater utilities, Clean Water Services must treat effluent to meet regulatory requirements before discharge into the environment. However, the Tualatin's slow flow and seasonal variation made diluting wastewater with river water legally (and environmentally) impractical: sometimes the effluent produced was too hot or eclipsed the river's own water levels. For example, in the summer of 1969, the utility estimated that 97 per cent of the river's water consisted of effluent ([CWSAC 2010](#)). From the 1970s to the 1990s, changing federal and state regulatory structures and environmental litigation ([Krantz 2001, 10](#)), pushed Clean Water Services to investigate different approaches for treating wastewater before environmental discharge.

In 2004, Clean Water Services received permission from the Oregon Department of Environmental Quality to integrate its watershed management and wastewater treatment programs, two areas previously covered by different permits (CWS 2022). The utility transformed its wastewater lagoons into a wetlands “natural treatment system” (CWSAC 2014a; c.f. Muckerheide 2012) that produced water clean enough that, “with some additional technologies would meet purity standards for the high-tech industry (higher standards than for drinking water) or as a product ingredient,” as well as providing new recreation opportunities (CWSAC 2014a). The constructed wetlands system developed mimicked historic wastewater disposal approaches by positing wetlands as a recipient for wastewater (Vymazal 2011; Tarr 1996). However, the “constructed” approach adopted by Clean Water Services differed from historical uses by creating an engineered environment that draws on well-established twentieth-century water treatment approaches of sedimentation, use of anoxic/anaerobic as well as aerobic zones, and filtration (Vymazal 2022). By combining the old and the new the utility was able to pivot towards a more environmentally—and financially—palatable objective while complying with new regulatory limits.

The utility still had to demonstrate that recycled water could meet industrial needs as well as the necessary standards for human contact and ingestion. Those efforts took a nonlinear turn thanks to Clean Water Services’ commission member Art Larrance (CWSAC 2013; Larrance 2018). Larrance is considered one of the key actors in Oregon’s craft beer revival for his role in helping legalize beer consumption at breweries (HB 2284, passed in 1985), and for co-founding the Oregon Brewers Festival in 1988 (ibid.). In 2013, 38 years after changing Oregon’s legal landscape around beer—and kicking off the microbrew/craft brew revolution across the US—Larrance was appointed to the utility’s advisory commission (The Oregonian 2024). Within the year, Larrance suggested to other members of the commission that “if you want to talk about water, you ought to make beer” (Leone 2014). The idea stuck. Clean Water Services invited homebrewers to participate in the inaugural “Sustainable Beer Challenge: Pure Water Brew Competition” (ibid.). Initially, the utility planned to demonstrate the effectiveness of its technoscientific practice of caring for wastewater by taking water directly from the treatment plant. Oregon DEQ regulations, however, prohibited consumption of wastewater, no matter its purity (CWSAC 2014b). The utility pivoted to indirect reuse, collecting river water that included approximately 30 per cent effluent, and then treating the water with an additional high-purity treatment step before distributing it to home brewers (ibid.). In doing so, they demonstrated that then-current regulations already offered a window for reuse.

Although the inaugural challenge received significant (and largely positive) press attention, Clean Water Services did not immediately push for widespread adoption of DPR. Rather, due to “regulatory concerns about setting a precedent for direct potable reuse in general,” the utility focused “on getting permission to produce small batches of high purity water for specific uses such as brewing,” leaving for future work the “larger general question of direct potable reuse with state and federal regulators” (ibid.). In 2015, efforts to secure a permit for a second brew challenge facilitated de-facto public outreach for the brewing showcase as hearings and an open comment period on a proposed permit garnered additional news coverage (e.g. Tims 2015), industry-group attention (e.g., Albrich 2015), and eventually legal permission to use treated effluent in a beverage produced for human consumption (CWSAC 2016). Through incorporating beer as part of its public outreach, Clean Water Services made the otherwise mundane legal matter of defining water quality relevant to a wider audience. In other words, the utility repoliticized older knowledge

and technologies, while incorporating historical forms of water evaluation in a new light to reorient their publics towards new conceptions of water quality.

Beer brewing as outreach does not easily scale to the macro level. It happens rather at the meso-level via interactions undertaken by multiple stakeholders across the water, wastewater, and regulatory realms at primarily regional levels due to constraints imposed by each state's regulatory landscape. Following Clean Water Services' legal and public success with its outreach efforts, other utilities and even membrane filter manufacturers adopted the use of beer brewed with recycled water as an entry point for convincing stakeholders that DPR is an appealing solution to the problem of water shortages. As each US state has its own permitting process, brewing challenges in California, Arizona, and other areas considering reuse have required a multifaceted process of communicating with local and regional communities, as well as state-level regulators. The 2017 AZ Pure Water Brew Challenge (Pima County, AZ) and 2019 One Water Brew Fest (Scottsdale, AZ) both required new permitting structures; for example, the Arizona Department of Environmental Quality granted Scottsdale's permit only after multiple years of working to repeal a state-wide prohibition of direct potable reuse (see [Manheim 2024](#)). Temporary permits to brew beer with DPR water have opened the door to legislative changes: in August 2024 California approved potable reuse regulations ([WateReuse.org 2024](#)), and Arizona wrapped its comment period on rulemaking.

It is at the intersection of craft beer brewing and wastewater treatment that the retooling inherent in programs promoting DPR emerge. The use of wastewater as a resource is not new. However, increasingly strict regulations governing wastewater discharge have combined with a political desire to identify "new" sources of water under extended drought conditions. From a technical standpoint, potable reuse promises to respond to both demands. Long-standing cultural taboos and legal restrictions around wastewater have complicated that effort. In response, engineers and others have sought to retool definitions of water quality, arguing that water quality be defined by its (scientifically measured) end characteristics rather than by its source. To materialize that argument, they tactically—albeit serendipitously—redirected outreach efforts to include partnership with craft beer brewers. These partnerships demonstrate how tactical redirection of already-existing technologies (e.g., beer brewing) can facilitate sociotechnical change. In the process, how local publics, and state-level legislators, actors in the brewing industry and other food-related industries, understand and evaluate the quality of water produced from waste(water) increasingly reflect a "One Water" approach.

Case 2: Sugarcane Biofuels: From Sugar to Sustainability

Brazil is the largest producer of sugarcane in the world. The crop has played a key role in the country's political and cultural formation over the last five hundred years ([Sigaud 1979](#)) and continues today as a leading agricultural product. This case study, based on research by Katie Ulrich, examines how Brazilian sugarcane actors have directed the sugarcane industry's survival amid shifting political, economic, and environment contexts over the past half-century. These actors, who include mill owners, sugarcane growers, and university and industry breeders and researchers, have done so through retooling old technologies like fermentation, as well as retooling liabilities around water and waste. In the process, they have refashioned the place of the sugarcane industry in Brazil. Put another way, the Brazilian sugarcane industry has always been a political project, and industry actors have retooled technologies and production processes in order to navigate that political project through shifting conditions. In doing so, they have



reoriented the industry in sometimes unexpected directions—for example, transforming the sugarcane industry into one no longer centered around sugar, and most recently mobilizing what remains a massive monocrop endeavor in the service of sustainability efforts.

Sugarcane has been cultivated in Brazil since Portuguese colonizers introduced the crop in the early 1500s. Since then, the sugarcane industry has undergone many technical, social, and political changes. Early colonial expansion centered around the commodity of refined sugar, which was enabled by significant deforestation, land dispossession, and enslaved labor ([Ferlini \[1984\] 2017](#)). Slavery was abolished in 1888 and replaced by indentured servitude and other forms of precarious labor ([Scheper-Hughes 1992](#)). From the nineteenth century, mill owners with the support of the state undertook various efforts at modernization; today the majority (though not all) of sugarcane production in Brazil is characterized by industrialized technologies, such as mechanized harvesting ([Cano 1977](#); [Dean 1969](#)). In the mid-twentieth century the government and industry implemented extensive sugarcane breeding and research programs ([Elias 2003](#)). Workers and impacted communities who live near the seas of sugarcane fields covering the landscape in many parts of the country have for centuries brought attention to the negative environmental, social, and health impacts of sugarcane monocrops. This has led to legislation limiting to some extent the crop's expansion and certain labor practices ([Alves 1993](#)).

While many of these shifts involve technological change and can be located within transforming political and economic circumstances, here we focus on two moments that highlight sugarcane industry actors' efforts to direct the future of the industry through retooling technologies and production processes. These moments are the introduction in the 1970s of sugarcane-based biofuels as a major second commodity in addition to refined sugar, enabled by the authoritarian government's national development policy; and recent projects to advance the sustainability of sugarcane cultivation in the face of climate change through crop breeding that changes how sugarcane utilizes water.

Retooling Fermentation amid Authoritarianism and Market Crises

Sugarcane cultivation in Brazil from the start centered around the commodity of refined sugar, made by pressing sugarcane juice from the stalks, boiling it down, and refining the resulting sucrose. Sugar drove the colonial economy in Brazil and then the Caribbean, remaking the world into industrialized modernity ([Mintz 1985](#)). But sugar was far from a reliable commodity for mill owners. From the seventeenth through twentieth centuries, Brazilian sugarcane elites negotiated volatile sugar prices in global and domestic markets, as well as crises of over- and underproduction. As they gained increasing political clout, they lobbied the government for interventions. The 1930s saw some early successes in the form of government-mandated quotas, as well as modest government support for developing an alternative commodity, ethanol biofuels ([Eaglin 2022](#)). Sugarcane actors were interested in biofuels as they would provide mills another path to revenue if sugar prices were low or the sugar market was oversaturated.

Biofuels are made by pressing sugarcane juice from the stalks and then, rather than boiling and refining it into sugar, fermenting the juice using yeast. As yeast metabolize the sugar they produce carbon dioxide and ethanol. Sugarcane growers had already fermented sugarcane juice to make *cachaça*, a sugarcane brandy, since sugarcane was first cultivated. Even though the actors at large sugar mills producing refined sugar had not always been the same as those at the smaller distilleries making *cachaça*, fermentation was far from a novel technology for the former.

After further incremental government support for developing biofuels, sugarcane elites' lobbying finally culminated in a major national biofuels policy in the 1970s amid a severe collapse in sugar prices. Called ProÁlcool, this policy was launched by the military dictatorship as part of an explicit national development agenda ([de Paul et al. 2012](#); [Barreto 2018](#)). ProÁlcool financed the retrofitting of mills with fermentation equipment and provided other market incentives to spur a biofuels market, like set biofuels and gas prices ([Nunberg 1986](#)). Loans through ProÁlcool for sugar mill owners to construct new equipment had interest rates less than a quarter of what was typical during the period. One representative mill in the state of São Paulo received an initial loan of Cr\$119,075,000 (over USD\$11 million), which was later doubled, and the low interest rates "made the loans a rather substantial money transfer more than a loan" ([Eaglin 2015, 175–6](#)).

The effects of ProÁlcool were massive. By the mid-1980s, sugarcane cultivation had more than quadrupled, with significant portions going toward biofuels production ([ibid.](#)). Today, Brazil is the world's largest producer of sugarcane-based biofuels, and a close second in all biofuels after the United States' corn-based biofuels. Currently about half of Brazil's gasoline demand is replaced by biofuels, and almost all light vehicles have flex-fuel engines that can take either gas or ethanol ([Bennertz 2014](#)). When drivers go to the fuel station, especially in states like São Paulo where sugarcane is concentrated, they see two prices on display and have two pumps to choose from: one for gas and one for biofuels. For many consumers in Brazil, biofuels are a mundane and well-known fact of life.

For many in the sugarcane industry, ProÁlcool was the most significant change to sugarcane in the twentieth century. It gave mills an unprecedented flexibility to produce and sell either sugar or biofuels depending on the daily market prices of each. Sugarcane was not just for sugar anymore. Such flexibility remains an explicit discourse among industry actors, who credit ProÁlcool and sugar-biofuels *flexibilidade* with the sugarcane industry's continued survival. This flexibility was far from a given or inherent property of the industry ([Ulrich 2025](#)). It was a deliberate project by sugarcane elites who gained the support of the authoritarian government to reorient the sugarcane industry's place in the Brazilian and global economy. By reorienting its place, they remapped the sugarcane industry's future—not only the shape of this future but its very possibility, in the eyes of many. On the military government's part, ProÁlcool was a means to carry out national development, including a turn to domestic energy production to promote energy independence in the context of Middle East oil crises ([Nunberg 1986](#)).

For both industry actors and the government, at the heart of such reorientations was the retooling of an old technology, fermentation. What was new or innovative was not the technology per se but rather how sugarcane industry actors, with the support of the government and ProÁlcool, mobilized fermentation in fashioning a new economic arrangement for the sugarcane industry. At stake was not simply a new product, biofuels, but the flexibility it conferred. The flexibility to switch between refined sugar and biofuels on an immediate basis to respond to shifting political and economic conditions fundamentally transformed sugarcane's industrial arrangement. This secured the industry's future viability in the minds of sugarcane elites, even if—perhaps less expectedly—such a future pivoted partly away from the heart of the industry's five-hundred-year history, refined sugar. This is the intentional yet nonlinear reorientation at the meso level via the not-quite-new that we seek to surface with the concept of retooling.

Retooling Water's Limits and Liabilities in Service of Sugarcane Sustainability

Environmental concerns were not entirely incidental to the implementation of ProÁlcool and the boosting of a non-petro fuel source. Yet they are generally understood to have been secondary to the political and economic objectives described above. Toward the end of the twentieth century this changed: the Brazilian government, like others around the world, started supporting biofuels as replacements for fossil fuels. Environmental groups continued to raise concerns about the impact of sugarcane monocropping on local communities and their environments, as well as deforestation. In response, the sugarcane industry over the last couple of decades has reconfigured and centered its relationship with sustainability. In one example that we focus on here, sugarcane mill owners and researchers, including those breeding cane at university or government-funded centers, retool the role of water in sugarcane cultivation. In doing so they once again reorient the industry's place in the country's social and environmental futures, reshaping the industry into one in service of sustainability.

Sugarcane is a thirsty crop, accustomed to tropical or semitropical climates. In the Center-South region of Brazil, where the majority of cane is cultivated, rainfall has historically been sufficient. Irrigation is far less common there than in the Northeast, where sugarcane was originally cultivated and which still has a significant sugarcane industry ([Dias and Sentelhas 2019](#)). Yet even in the Center-South, sugarcane growers are increasingly concerned about climate-change-intensified droughts. Researchers have ramped up efforts to develop drought-resistant varieties. They're also exploring another strategy that retools the very nature of water in cane cultivation processes in the first place. This strategy centers on the utilization of fertigation, a technological process that combines fertilization and irrigation via irrigating with a liquid fertilizer.

To understand the desirability of fertigation, it's also necessary to understand how it serves a dual purpose for sugarcane producers—not only as combined fertilization/irrigation, but also as waste management. When biofuels are produced, one major waste product is vinasse. Vinasse is a dark reddish-brown liquid with a pungent, sweet-sour aroma that's generated during the fermentation process. It's rich in potassium and nitrogen. And there is a lot of it: twelve to fourteen liters of vinasse are produced for every liter of biofuel. As a result of the rapid growth of biofuel production following the implementation of ProÁlcool, the output of vinasse also grew proportionately, and thus, too, the question of how to dispose of it. In the first few decades of biofuel production, mill owners dumped vinasse into rivers near the sugarcane fields, the cheapest option. However, as research made clear the detrimental impact on water quality, environmental regulations barring this practice were increasingly implemented after the turn of the twenty-first century ([Christofoletti et al. 2013](#)).

Sugarcane mills have since experimented with various ways to deal with the “huge problem” that is vinasse, as one industry actor described it to me. They've concentrated and evaporated it to make animal feed. They have also burned it to produce biogas ([ibid.](#)). The most common current technique for dealing with vinasse, though, is fertigation. The vinasse is piped underground from the sugarcane mill to open ponds a few hundred meters away. Foamy and warm (60 degrees Celsius) due to metabolic activity, the vinasse is concentrated, mixed with additional fertilizers, and piped into trucks that then take it to nearby fields. There, other trucks ride up and down the sugarcane rows sprinkling the vinasse over the plants; in some cases, cannon sprinklers or drip irrigation piping are also used ([Fuess et al. 2017](#)). Vinasse fertigation is typically only applied to nearby fields, as it is too cost-prohibitive to transport to fields farther away.

With vinasse fertigation increasingly established, sugarcane researchers and breeders have found in it a new potential tactic for securing the crop's future in the face of climate change. Namely, they're developing cane varieties that more effectively utilize vinasse during fertigation, selecting for traits that improve sugarcane's ability to uptake and metabolize it. Breeding sugarcane requires, as one interlocutor explained, a crystal ball for looking into the future. Due to sugarcane's genetic complexity—scientists describe it as the most complex crop in the world, in part because of hybrid crossing that started in the colonial era—transgenic modification is still relatively rare. New varieties are primarily created through conventional breeding, which involves selecting, amplifying, and combining desirable traits among existing strains. It takes fifteen to twenty years after a cross for the new variety to be ready for cultivation, so when breeders start a cross, they are anticipating what will be a desirable trait in twenty years. Through this anticipated desirability, they figure the future, and then inscribe that future in the cane's genome.

Cane's refigured future emerges as one centered on both drought resistance and waste utilization. Mill owners and researchers position fertigation-optimized strains as an exemplar of waste/water recycling, gaining an association with more environmentally minded water practices as explored in the case on direct potable use in the United States described above. Sugarcane actors tout the crop's entry into a circular bioeconomy, advancing cane as a sustainable raw material for plant-based fuels. They have used crop breeding to retool (waste)water from a limitation or liability to an asset amid the looming threat of water scarcity and environmental restrictions on vinasse dumping. Not simply utilizing waste, they reorient the sugarcane industry toward a new place in Brazilian social and political life: as a leader in sustainable futures.

The actual sustainability of the technologies underlying vinasse remain contested, but we highlight how it is through a process of retooling the role of (waste)water in production processes that sugarcane producers and researchers redirect the industry in response to shifting political and social conditions, including concerns about climate change. They secure the future of the industry by once again redefining its future, pivoting in non-obvious ways such as promoting a historically environmentally damaging monocrop in service of sustainability. Here as with ProAlcool, sugarcane actors retool existing technologies and production processes, thus refashioning the place of the industry in Brazil and even the world. It is through an intentional yet nonlinear retooling amid shifting sociopolitical conditions that they reconfigure the nature of the political project that the sugarcane industry has always been and will be.

Conclusion

Both case studies presented above involve some level of technical innovation. Still, they also rely heavily on well-established techniques, some of which date back decades or even centuries, to achieve their goals. Innovation is not absent, but it is not the sole or even most important process at work. Incremental improvements in the efficiency of water purification may marginally contribute to the success of these techniques in the present environment, while the effort to breed new varieties of sugarcane to meet the future challenges of climate change is an essential contributor to the imagined promise of fertigation. Yet it is not improved technological capability that drives these technologies' newfound popularity. Rather, it is the desire to respond to different political aims, coupled with the promise to possibly improve upon the current state of affairs. It is also clear that, in a broader sense, these sociotechnical interventions maintain the status quo—that is, dense urban-industrial populations in an arid environment, in one case, and a profitable sugarcane industry, in the other.



At the same time, in the context of infrastructural decay and underinvestment, the promise of side-stepping or even disrupting existing systems, rather than solely maintaining them, gives these techniques their allure. In the case of DPR, it fuels regulatory support for transforming wastewater into an entirely “new” source of clean drinking water at a time when conventional sources and infrastructures are under pressure—perhaps even enough excitement to overcome the “yuck factor.” In the case of sugarcane, the elusive possibility of a circular system that will be sustainable and climate-change-proof drives ongoing investment and reinvention. In these cases, alluring futures give new meanings and uses to old technologies. These retoolings are intentional projects, not accidents; they develop in nonlinear ways; and they operate mainly at the meso-level of social organization.

Attending to retooling as a form of change that is constitutive of sociotechnical transformation can strengthen our analyses and intervention in collective action. People engaged in processes of change are constantly mobilizing what is to bring about what they think should be. In this regard, retooling offers an alternative to the ideals of modernist planning (i.e., the notion that plans manage both short-term and long-term risks) as well as diagnoses of radical contingency (i.e., the idea that planning is never entirely possible). As an analytic, retooling disabuses us of any remnants of the idea that society is *terra nullius*, waiting to be transformed, or any traces of the assumption that there is little to no choice when designing processes of sociotechnical change. During turbulent times, moments when it seems everything is changing and yet nothing has, retooling opens actionable avenues for change.

We have developed the concept of retooling to highlight how such projects of technical change simultaneously articulate innovation, maintenance, and repair. We have shown how such projects activate the old and the new as they engage in transformations aimed at political objectives—e.g., deal with water scarcity, respond to climate change. Retooling draws on established technologies to activate different futures; it does so by intentionally redirecting existing approaches with the understanding that the end result may shift how life is lived in specific places. Retooling highlights continuity and change at once. In our turbulent twenty-first century, retooling has moved to the forefront as a modality of sociotechnical change. As such, we suggest that STS scholars may find retooling a pragmatic and politically promising theoretical tool for our times.

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