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Chemistry, Green Chemistry, and the Instrumental Valuation of Sustainability

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Abstract Using the Public Value Mapping framework, I address the values successes and failures of chemistry as compared to the emerging field of green chemistry, in which the promoters attempt to incorporate new and expanded values, such as health, safety, and environmental sustainability, to the processes of prioritizing and conducting chemistry research. I document how such values are becoming increasingly "public." Moreover, analysis of the relations among the multiple values associated with green chemistry displays a greater internal coherence and logic than for conventional chemistry. Although traditional chemistry research has successfully contributed to both economic and values gains, there have been public values failures due to imperfect values articulations, failure to take a longer-term view, and inertia within a system that places too much emphasis on "science values." Green chemistry, if implemented effectively, has potential to remedy these failures.

Keywords Green chemistry · Public value mapping · Science policy · Chemistry

Introduction

Chemistry and chemical products are an integral part of the U.S. economy. According to one study, the chemical industry accounts for 1.7% of U.S. GDP, directly creates 868,700 jobs, and contributes to 4.8 million additional positions (ACS 2007). Chemistry research has enhanced health and quality of life, fostering key discoveries in pharmaceuticals, materials, and consumer products. While these

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advances have aided and contributed to the country's growth, the development, manufacture and use of some chemicals has increased the vulnerability of people and ecosystems to the negative effects of production and exposure. Commercial chemistry processes often include high water and energy inputs, dangerous working conditions, and harmful feedstocks and products. Chemistry research, both academic and industrial, can carry the dangers of exposure. At the extreme, industrial chemistry has contributed to large scale scares, such as that surrounding the use of Alar on apples, and public health disasters like the Bhopal Disaster in 1984, during which a chemical release at a Union Carbide plant killed thousands of people. Thus, one of the central challenges of pursuing chemistry for its positive outcomes is balancing these against the associated risks.

Part of the impetus behind chemistry research and development in the United States comes from federal spending on science and technology. Between 1950 and 1999 the total government input into R&D was 3.2 trillion dollars (2,005 dollars) (Thurgood 2006). Funding specifically targeted to chemistry has risen from $821 million in 1997 to $1.447 billion in 2007. In 2007, chemical engineering also received $602 million. Chemistry and chemical engineering together consisted of 4.1% of non-defense federally funded R&D (Rovner 2009). Many of the larger federal science agencies, including the Department of Defense, National Science Foundation (NSF), National Institutes of Health, and Department of Energy, devote resources to chemistry and chemical engineering. Because much of chemistry research is justified on the promise of improved quality of life, while the pursuit of such improvements may also bring increased hazard, chemistry provides a fertile test-bed for a critical examination and assessment of the public values associated with an important scientific field.

Within the suite of public values concerns, sustainability has arisen as a policy issue for nations, international institutions, and non-governmental organizations. As groups such as the United Nations,[1] the U.S. Environmental Protection Agency (EPA)[2] and National Academy of Sciences[3] have emphasized sustainability and environmental health, approaches like green chemistry have emerged and grown as proposed means of ameliorating the environmental and safety impacts of current approaches to chemistry. Green chemistry, increasingly offered as an alternative to traditional chemistry, focuses on replacing the wasteful or harmful processes and products that contribute to hazard. Supporters of green chemistry claim it can become a viable alternative to traditional, or "brown," chemistry through the institution of academic programs, the appropriation of research funding, and the implementation of green chemistry practices in industry. Green chemistry is distinct from the idea of environmental chemistry, which is closer to the end-of-pipe solutions that government regulatory programs have historically pursued. Although both focus on the amelioration of negative environmental effects, environmental chemistry can focus on the reduction of negative impacts after chemical production, while green chemistry explicitly deals with the reduction of harm by considering

[1] http://www.un.org/esa/dsd/dsd/dsd_index.shtml (last accessed 9/10).

[2] http://www.epa.gov/sustainability/ (last accessed 9/10).

[3] http://sites.nationalacademies.org/PGA/sustainability/index.htm (last accessed 9/10).

risk during research and production. Green chemistry is currently growing in both adherents and influence, but is still minuscule in comparison to the broader discipline of chemistry.

This paper contributes to the growing effort to explore, expand, and apply the emerging theories and methods of Public Value Mapping (PVM; Bozeman 2002, 2003; Bozeman and Sarewitz 2005; this issue). First, it applies PVM to a new type of empirical case—a disciplinary field of research and it identifies a new source of public values articulation—science textbooks. Second, it documents the ways in which values associated with green chemistry have become increasingly "public," while not yet achieving the status of common public value. Third, it explores new manifestations of public value failure, including differences in failures in instrumental versus intrinsic values,[4] and new criteria for assessing public value failure. And finally, it documents how the relations among values differs between conventional and green chemistry, and relates those different relations to green chemistry's greater capacity to effectively pursue a wider range of public values.

Green chemistry's central premise strikes close to the ideas behind public value mapping. Both seek to look beyond obvious market successes to address the considerations that market measurements cannot. Green chemistry is an appropriate case for study of the PVM framework because it, first, articulates a public values set that its supporters claim is more robust than that of traditional chemistry and, second, works towards implementing alternative policies, providing the field with its own public values challenges.

Green chemistry proponents claim it can prove as effective as mainstream chemistry for the economy, for quality of life, and for materials production, while being superior in terms of environmental impacts, efficiency, and safety. The successful green chemistry researcher considers both the utility of a molecule and the external costs of chemical production, including pollution or health consequences. In evaluating green chemistry and its relationship to traditional chemistry, I examine, first, the value distinctions that green chemistry offers and, second, the trends and prospective future for the field. Next, I discuss the implications for green chemistry in terms of both market successes and in reaching its public value goals. Finally, I explore prospective pathways for green chemistry policy, and how it can develop in its relationship to traditional chemistry.

Imputed Public Values

The value goals of a given field or endeavor define an aspirational set of criteria by which one can, first, assess how appropriate the endeavor is to enhancing the values it promotes and, second, how operations may actually begin to meet those goals (Bozeman and Sarewitz 2005; also see Bozeman and Sarewitz, this issue, for further discussion of theory and method behind public values and public value mapping).

[4] Intrinsic values represent valued outcomes that are the ends of an endeavor, whereas instrumental values represent the means to reaching an intrinsic value goal. Bozeman (2007) provides the example of vaccination as an instrumental value that can enhance the intrinsic value of public health.

PVM dictates assessment beyond the standard metrics of market success/market failure. An activity can be a market success, but still fail on public values criteria, such as health, wealth creation, or distribution of power. Bozeman and Sarewitz (2005) provide one example of a black market for organs, which can operate as a market success, where harvested organs go to the highest bidders, but which also fails to account for public values focused on providing equitable healthcare. In the chemical industry, chlorofluorocarbons (CFCs) once provided both a public value and market success, in that they were a safe, effective, affordable alternative to more dangerous chemicals. However, while the market value of CFCs remained positive, the public value was contested with growing awareness of CFCs' contribution to depletion of the stratospheric ozone layer. The realm of synthetic organic chemicals provides abundant examples of market success/public value failures. There are tens of thousands of synthetic chemicals in production and use, and hundreds of new ones every year, that have produced useful effects and monetary reward. At the same time, they have been named as one contributor to "human domination of Earth's ecosystems" (Vitousek 1997), and have led to negative impacts, as is the case with insecticides like DDT and polychlorinated biphenyls.

The public values realm of both chemistry and green chemistry are defined by the setting of federal policy, through regulations and appropriations, and by the institutions and individuals acting within the field. At the federal level, green chemistry is still a nascent undertaking. Thus, much of the definition of the field occurs in academia, non-governmental groups, and industry. On the other hand, chemistry as a whole is well-established, massive in reach, and diverse. Neither federal definitions, nor any one set of value goals, can accurately define the whole field. However, since the shapers of green chemistry have promoted the idea as an alternative value set to those of traditional chemistry, some exploration of chemistry values, even in broad brushstrokes, can provide a foundation for PVM.

I have assessed the fields' general values, and especially those of academic chemistry, through chemistry textbooks. In making the case for the value of chemistry, textbooks typically state the public values that the field can meet. These public values will not be fully representative of chemistry, since they do not include statements by chemistry policy-makers and other influential groups, and public value changes or additions made in industry or elsewhere. However, they do provide an appropriate proxy for the public values set. Anyone who studies chemistry casually, or who enters a career in chemistry research, encounters them. The textbooks represent the authors' attempts to represent the field to future chemists, and may help to shape their viewpoints. Thus, at the same time they shape the values that new chemists are supposed to associate with chemistry, they also represent the values expressions of more experienced chemists, the authors. The textbooks guide inquiry by providing a set of goals that are upheld as exemplars of the field. For this research, I have chosen textbooks that are popular, influential, or both.

I examined several current prominent chemistry textbooks, including a general chemistry textbook that is the 7th top seller in the reference section of Amazon.com's Science & Technology store, popular organic chemistry textbooks, and older prominent chemistry books. The chemistry textbooks I examined focus on knowledge production and education as the primary values of chemistry. However, they also discuss the ancillary benefits of chemical research, including environmental remediation and quality of life improvements, including wealth creation.

One of the current chemistry textbooks (Zumdahl 2006) argues that studying chemistry is of value because of the topic's universality, its ability to enhance knowledge and facilitate the learning of life skills, and its contribution to impacts in all sectors, from health care and medicine, to industrial materials, to amelioration environmental problems. More than discussing chemistry's impact for any one sector or set of impacts, the authors stress the widespread applicability of chemistry research.

Another recent textbook, *Introduction to General, Organic, and Biological Chemistry* (Ouellette 1997), defines the chemistry process so that the links between instrumental values, and the intrinsic values they enable, are clearly evident. According to the text, chemistry is a process which leads to insight, through which people can control the environment, thus improving the "quality and quantity of food, clothing, and shelter" (p. 1) With this ability chemists can enhance the value of the environment, can refine the earth's naturally occurring substances, and can contribute to medicine and other issues of "life, sickness, and death" (p. 2) Neither textbook stresses chemical research or production as potentially dangerous or environmentally harmful.

Although the positive environmental value of chemistry does not emerge as often in older texts, the other public values are similar. I examined Linus Pauling's textbooks because they were written by one of the most influential chemists of the 20th century, and are still in the top 100 chemistry reference books (based on Amazon.com sales rankings). Pauling's 1975 textbook, *Chemistry*, describes the field, first, as a way to increase understanding and knowledge, and, second, as an "instrument for biology, medicine, and human nutrition" (Pauling 1975) that enables progress through the "power of man over matter" (p. 1). The textbook also contains general value statements, ranging from making "the world a better place to live in," increasing quality of life, and "enlarging the sphere of their activities" (p. 2) since chemistry has consistently achieved this through advancements like pharmaceuticals, anesthesia, rubber, and steel. Pauling's 1953 textbook, *General Chemistry*, aimed at more advanced students, limits its value set only to enhancing knowledge, understanding, and education through the teaching of argument, deduction, induction, and the scientific method (Pauling 1958).

Other groups express similar value claims. For example, the NSF Chemistry Division, which largely funds academic chemistry research, states that its mission is "to promote the health of academic chemistry and to enable basic research and education in the chemical sciences." The mission statement does not mention the more material benefits of chemicals.

The American Chemical Society (ACS), a Congressionally chartered group that is also the largest scientific professional organization in the world, does integrate concerns beyond knowledge creation. In trying to represent its 154,000 members from academia and industry, the ACS has included a broad set of values in their rhetoric. While the mission speaks to the general goal of "[i]mproving people's lives through the transforming power of chemistry," its more specific values include "public health, protecting the environment and contributing to the economy." While it does not (in contrast to green chemistry) propose a method for achieving these goals, ACS explicitly discusses values outside of the market.

While they tend to emphasize environment and human health less conspicuously than green chemistry, the values articulated as justifications for many areas of mainstream chemistry are similar to those of green chemistry. The intrinsic values in many areas of chemistry focus on knowledge and quality of life, and these are important for green chemists as well. However, we will see that the large differences emerge when instrumental values are considered. Instrumental values are the means by which one can achieve intrinsic values. Through its very different form of values articulation, green chemistry proposes an implementation of its value structure that strives towards its intrinsic values through specific instrumental values that explicitly link the process of doing chemistry research with the desired outcome of sustainability. This call to examine such values throughout the process, rather than as one desired outcome among several, sets green chemistry apart. Additionally, green chemistry stems from the claim that, while the intrinsic values of traditional chemistry are desirable, it works under several unspoken, perhaps unrealized instrumental values that guide chemistry inquiry towards a less sustainable path.

The instrumental values that lead chemistry towards environmental hazards are typical of the way chemistry has historically been conducted and taught. They likely originated in the historic ease and low expense of using abundant materials like petroleum-based feedstocks, from educational emphasis on sometimes-wasteful stoichiometric reactions, and from insufficient awareness of toxicity. According to green chemists, lack of consideration for these factors has led to environmental and health problems that are avoidable if chemists follow alternative strategies for producing chemicals. According to one social scientist, "Very substantial damage to environment, workers, and users of chemicals resulted from the actions of chemists and chemical engineers (in collaboration with others) in the 20th century. Many or most of those chemists and chemical engineers devoted relatively little attention to investigating, publicizing, or protecting against the risks of the chemicals with which they worked or the chemical products they helped make available for commerce"[5] (Woodhouse 2003). While some areas aimed at reducing the risks of chemistry, like industrial toxicology and worker hygiene, did see growth in the 20th century, such approaches remained external to the articulation of public values and practice of the science.

One green chemist related an anecdote concerning his undergraduate chemistry career to highlight the unquestioning relationship between mainstream chemistry research and chemistry hazard: "When I was a student … I asked a professor, 'Is chemistry dangerous? Will I be putting myself and my future family in harm's way if I choose chemistry as a career?' Do you know what the answer was? 'If you're asking yourself that question, get another major.' We accept that chemistry has to be dangerous, so 'that's just part of the job there, John'" (Warner 2008). In this framing, chemists are either not considering safety to have value, or are conceptualizing risk as integral to the role of the chemist. According to the green

[5] http://www.rpi.edu/~woodhe/docs/green.html#N_1_ last accessed 7/09.

chemistry viewpoint, the value expressions of mainstream chemists are either incomplete or incorrect. People like the unnamed professor put value, if sometimes unvoiced, on neglecting considerations of risk.

This status quo value structure shares characteristics with disciplines across the scientific enterprise. These "science values" represent the dominant post-World War II axiology that stresses "pure," or undirected fundamental research, theory-driven work in the physical sciences, and a linear model in which the most significant instrumental value for scientists is to conduct sound science (Weinberg 1971; For further development of the idea of science values and their relation to public values, see Meyer, this issue). Values such as health, economy, and national defense may be expressed as intrinsic values to which the science will eventually apply, but the value stress, and policy emphasis, remains on the conduct of basic scientific research. Since the researcher is supposed to focus on the scientific goal, other outcomes, even negative ones, might be classified as byproducts of academic research, or even industrial processes, which do not fall under the scientist's responsibility. One of the main claims of green chemistry is that it "shifts the approach to addressing issues, such as environmental problems, from the *circumstantial* to the *intrinsic,*" by infusing the research process with other values. (Anastas 2003, p. G29, emphasis in original).

Of course much of chemistry, especially industrial chemistry, is not principally motivated by science values, but rather seeks to advance values that can be assessed monetarily. However, even when there is a concrete goal beyond knowledge, the primacy of scientific concerns, such as those reinforced by disciplinary tendencies and peer review, can drive neglect of other instrumental values during research and development. Green chemistry differs in that it stresses considerations like reducing waste, safety, and efficiency in conjunction with strong science and market success.

Green chemistry is a small concern among the many larger groups driving industrial chemistry. I take participation in the green chemistry community to be dependent only upon self-identification. Green chemistry as a field has very specific norms and principles, and the groups claiming to belong are cohesive and easily identified. I evaluate groups that claim adherence to the field's principles as belonging in the field. Green chemistry is a tiny piece of federal chemistry policy, a nascent but growing subdiscipline in U.S. universities, and a central tenet for some small research programs, start-ups, and boundary organizations. Promoters of the field are optimistic about continued growth and the prospect of increased federal involvement. Currently, many of the field's participants share a consistent vision on goals, and on how to reach them. One article remarks on the consistency in green chemistry's norms, along with its practitioners resistance to the intrusion of other, countervailing values, noting that "Green chemists are united in seeing themselves as advancing the values of health, safety, and sustainability—and decidedly do not perceive themselves as participants in chemical industry 'greenwashing'" and it "appears to be a genuine response from within the ranks of chemists and chemical engineers to address the role their professions play in environmental degradation and threats to human and ecosystem health" (Woodhouse 2005, p. 210). To date, the most active participants in green chemistry include the authors of the first text on the subject, Paul Anastas and John Warner, and the institutions they have been affiliated with, including their current research organizations, the EPA, the ACS Green Chemistry Institute (GCI), and the University of Massachusetts, Lowell Center for Sustainable Production. Such organizations are small; GCI has 8 staff members and the Lowell Center has 16, 4 of whom work in the Chemicals Policy and Science Initiative. Several other groups have been invested in the concept. Academic research institutions like the University of Massachusetts-Lowell, Berkeley, University of Oregon, and Yale have green chemistry centers, but not whole programs or departments. Some pharmaceutical companies devote a fraction of their effort to green chemistry, and participate in the Green Chemistry Institute's Pharmaceutical Roundtable. And several companies each year win the President's Green Chemistry Award.

In addition to the institutional leaders, smaller groups or individuals are active in green chemistry, working within academic chemistry programs or as sustainability-oriented segments of larger, more traditional industry concerns. While their participation is still integral to the growth of the field, I chiefly defined the set of public values from the framers of the concept and their organizations, and from other influential groups within green chemistry (Table 1).

Green chemistry attempts to expand the value payoffs of traditional chemistry to work more explicitly towards social and environmental benefit. The foundational articulation of the fields' values takes place in Paul Anastas and John Warner's 12 Principles of Green Chemistry (Anastas and Warner 1998) (see Box 1). Many of the organizations I examined have included or been involved with Anastas and Warner's principles (Table 2), and perhaps partially because of this, there is general consistency in the value expressions of many green chemistry proponents and institutions.

Rather than acting as a broad mission statement, these principles express strategies and approaches for pursuing successful green chemistry projects. Since prominent groups in the field use the principles as a jumping off point (Table 1), they can be taken as a source of foundational public values for green chemistry. Thus, from the first principle, the value is waste minimization. Others emphasize safety—"no toxicity," "less hazardous," "innocuous," "minimize the potential for accidents," efficiency—"renewable feedstocks," "atom economy," and environment—"prevent pollution," "minimize … releases to the environment." Within green chemistry organizations, perhaps because of the specificity of such principles, the value goals laid out by Anastas and Warner are consistently repeated. Although the instrumental goals may differ based on the nature and specific thrust of the institution, the intrinsic value of producing environmentally benign, efficient, non-toxic chemicals remains consistent. While some organizations and policy-makers may emphasize certain of the public value goals from the 12 principles over others, identification with the principles often occurs (Table 2). It should also be noted that these values are not yet officially "public." They are currently the community values of green chemistry community, which sets such values an aspiration of being codified in legislation and widespread implementation, and thus could become actual public values with time. The community values of green chemistry will either continue to be used by a limited community, or they are nascent public values that public policy action could institute.

Table 1 Public values expressions in green chemistry

Value	Sources	Example
Research, science	all	"Promote and coordinate Federal green chemistry research." GCRDA
Generate substances, products, processes	all	"Design syntheses to use and generate substances." A&W
Global economy	GC3	"Chemicals … are the platform upon which key elements of the global economy have been built." GC3
Cost effective	MichED, WB	"Society's needs can be met by processes and materials that …are cost effective, and are truly non-toxic and environmentally benign." WB
Effective	A&W, MichEd, GC3, GCRDA, WB	"Design chemical products to be fully effective." A&W
Better chemical choices	GC3	"Identifying existing and needed tools … for companies looking to make better chemical choices." GC3
Disseminate information	GC3, MichED	"Collect and disseminate information on green chemistry research, development, and technology transfer." MichED
Education	GC3, GCRDA, MichEd, WB	"Provide sustained support for green chemistry research, development, demonstration, education, and technology transfer." GCRDA
Open dialog	GC3	"Maintain an open, business-to-business dialog." GC3
Collaboration/cooperation	MichED, GCRDA, GC3	"In collaboration with … industry, academia, scientific and professional societies …" GCRDA
Promote green chemistry (or GC use)	GC3, GCI, MichEd, Yale	"Devoted to promoting and advancing green chemistry." GCI
Facilitate adoption	MichED	"Facilitate the adoption of green chemistry innovations in Michigan." MichED
Overcome barriers	GC3	"Sharing strategies to overcome barriers and reduce environmental footprints." GC3
Supply chain management	GC3	"Discuss and share information …as it pertains to sustainable supply chain management." GC3
Sustainable	A&W, GC3 MichED, GRC, WB, EW, EPA, Yale	"It would be preferable to have a sustainable supply, not only for current generations, but also for posterity." A&W
Environment	A&W, MichEd, WB, GRC, EW, EPA, Yale, MichED	Design syntheses to use and generate substances with little or no toxicity to humans and the environment. A&W
Reduce environmental footprints/impact	GC3, GRC, EPA	"Designed to reduce or eliminate negative environmental impacts." EPA
Renewable	A&W, Yale, WB, MichED	"Use renewable feedstocks." A&W
"Atom economy"	A&W, Yale, WB, MichED	"Maximize atom economy ….There should be few, if any, wasted atoms." A&W

Table 1 continued

Value	Sources	Example
Prevent waste	A&W, GRC, EPA, Yale, WB, MichED	"Design chemical syntheses to prevent waste."
Minimize pollution, pollution prevention	A&W, MichEd, EPA, Yale, WB	"Analyze in real time to prevent pollution." A&W
Little or no toxicity	A&W, EPA, WB, Yale, MichED	Design chemical products to be fully effective, yet have little or no toxicity. A&W
Reduce hazardous substances	A&W, MichEd, WB, GRC, EW, EPA, Yale, MichE	"Reduce or eliminate the use and generation of hazardous substances." A&W
Hazard reduction	A&W, MichED, GRC, GCI, GCRDA, Yale, WB	"Hazardous substances that can threaten human health and our environment should be reduced." (MichED)
Safe(r)	A&W,GRC, EW, EPA, GCRDA, Yale, WB, GC3	Identifying existing and needed information on toxics hazards, risks, exposures and safer alternatives. (GC3)
Minimize accidents	A&W, Yale, WB, MichED	"Substances … should be chosen to minimize the potential for chemical accidents …" A&W
Public health, human health	MichED, GRC, EW	"Public health and general welfare … are matters of primary public concern." (MichED)
Energy efficiency	A&W, GRC, EPA, Yale, WB, MichED	"Increase energy efficiency: Run chemical reactions at ambient temperature and pressure whenever possible." A&W
Innovation/ competitiveness	GRC, EPA, GC3, MichEd	"Green chemistry encourages innovation." EPA

Much of the overlap is due to explicit use of Anastas & Warner's 12 Principles in multiple sources. Sources: A&W = Green Chemistry: Theory and Practice (Anastas & Warner 1998); EPA = Environmental Protection Agency Office of Pollution Prevention; EW = (Woodhouse 2005); GC3 = Green Chemistry Commerce Council; GCI = ACS Green Chemistry Institute; GRC = Gordon Research Conference on Green Chemistry; GRCDA = Green Chemistry Research & Development Act; MichED = Michigan Executive Directive; WB = Warner Babcock Institute for Green Chemistry; Yale = Center for Green Chemistry & Green Engineering at Yale

The most prominent federal green chemistry policy to date has been the Green Chemistry Research and Development Act (GCRDA), which the U.S. House of Representatives passed, but the Senate never voted on. According to the GCRDA of 2007 (HR 2850), green chemistry exists to "design chemical products and processes that reduce or eliminate the use or generation of hazardous substances while producing high quality products through safe and efficient manufacturing processes" and supports "research, development, education, and technology transfer." According to one commentary on the bill, "It works to balance the real conflicts between economy and environment and between the present and the future" (Steinfeld 2002, p. 51). The act is consistent with the values of the twelve principles, and adds values of collaboration and cooperation (Table 1). As proposed legislation, the bill represents a not yet legitimized articulation of values for a nascent field, or an aspirational set of public values that has not been realized.

Box 1 The Twelve Principles of Green Chemistry (Anastas and Warner 1998)

1. **Prevent waste:** Design chemical syntheses to prevent waste, leaving no waste to treat or clean up.
2. **Design safer chemicals and products:** Design chemical products to be fully effective, yet have little or no toxicity.
3. **Design less hazardous chemical syntheses:** Design syntheses to use and generate substances with little or no toxicity to humans and the environment.
4. **Use renewable feedstocks:** Use raw materials and feedstocks that are renewable rather than depleting. Renewable feedstocks are often made from agricultural products or are the wastes of other processes; depleting feedstocks are made from fossil fuels (petroleum, natural gas, or coal) or are mined.
5. **Use catalysts, not stoichiometric reagents:** Minimize waste by using catalytic reactions. Catalysts are used in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and work only once.
6. **Avoid chemical derivatives:** Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.
7. **Maximize atom economy:** Design syntheses so that the final product contains the maximum proportion of the starting materials. There should be few, if any, wasted atoms.
8. **Use safer solvents and reaction conditions:** Avoid using solvents, separation agents, or other auxiliary chemicals. If these chemicals are necessary, use innocuous chemicals.
9. **Increase energy efficiency:** Run chemical reactions at ambient temperature and pressure whenever possible.
10. **Design chemicals and products to degrade after use:** Design chemical products to break down to innocuous substances after use so that they do not accumulate in the environment.
11. **Analyze in real time to prevent pollution:** Include in-process real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts.
12. **Minimize the potential for accidents:** Design chemicals and their forms (solid, liquid, or gas) to minimize the potential for chemical accidents including explosions, fires, and releases to the environment.

Anastas and Warner are both still active in the field, and continue to push the public value vision of their twelve principles. John Warner now leads the Warner-Babcock Institute for Green Chemistry. According to the Institute, green chemistry "seeks to unite government, academic and industrial communities by placing more focus on environmental impacts at the earliest stage of innovation and invention."[6] This definition, similar to the GCRDA, reiterates the goals of traditional chemistry ("innovation and invention"), but adds to them. The institute cites the twelve principles as the best means for implementing green chemistry. Anastas is the Director of the Center for Green Chemistry & Green Engineering at Yale University. The Center defines its mission as advancing the "theory and practice of green chemistry and green engineering,"[7] and defines green chemistry as a means to "reduce or eliminate the use and generation of hazardous substances"[8] also citing the principles. This consistency of vision serves, first, as a promotional tool for new green chemistry endeavors and, second, as a consistent expression of what it means to do green chemistry research.

[6] http://www.warnerbabcock.com/index.html last accessed 4/09.

[7] http://greenchemistry.yale.edu/about_the_center/ last accessed 4/09.

[8] http://greenchemistry.yale.edu/definitions/ last accessed 4/09.

Table 2 Expressions of the 12 principles by prominent groups in green chemistry

Participant	Expression
EPA	"The 12 Principles of Green Chemistry, originally published by Paul Anastas and John Warner in *Green Chemistry: Theory and Practice* (Oxford University Press: New York, 1998), provide a road map for chemists to implement green chemistry."
Green Chemistry and Commerce Council	"Green chemistry is an approach to chemistry that, through the use of the 12 Principles of Green Chemistry, reduces or eliminates the need for and generation of hazardous materials during the manufacture, design, and application of chemistry."
ACS Green Chemistry Institute	"The principles of green chemistry and green engineering provide a framework for scientists and engineers to use when designing new materials, products, processes, and systems."
GCRDA	"chemistry and chemical engineering to design chemical products and processes that reduce or eliminate the use or generation of hazardous substances."
Mich. Executive Directive	"'Green chemistry' means chemistry and chemical engineering to design chemical products and processes that reduce or eliminate the use or generation of hazardous substances while producing high quality products through safe and efficient manufacturing processes. Green chemistry is based upon the following 12 principles":
Warner-Babcock	quotes 12 Principles
Center for Green Chemistry & Green Engineering at Yale	quotes 12 Principles

Trends in Green Chemistry

This section explores the recent evolution of the field, to situate the idea of green chemistry within the current broader research context and to consider how the field might continue to develop. In the early 1970s, before the term "green chemistry" existed, Stanford Professor Barry Trost developed the idea of "atom economy." Atom economy is a means of accounting for "the limited availability of raw materials, combined with environmental concerns" (Trost 1991). The concept posits that a desirable chemical reaction is one in which the number of atoms coming out of a given process, as useful products instead of byproducts, are close in number to the atoms going in, resulting in a less wasteful, less polluting reaction.

To a large extent, Paul Anastas and John Warner have spearheaded the incorporation, expansion, and promotion of the atom economy idea. Anastas began supporting the idea when he instituted the EPA's Green Chemistry Program in the late 1990s. Between then and his current position at Yale University's Center for Green Chemistry & Green Engineering, he has also served at the White House Office of Science & Technology Policy, and as former head of the Green Chemistry Institute, which is now run through ACS. He is now at the EPA. John Warner has served as a professor in the University of Massachusetts system, and now heads the Warner-Babcock Institute for Green Chemistry. Together, the two wrote *Green*

Chemistry: Theory and Practice (Anastas and Warner 1998), which lays out the foundations of the green chemistry idea and fully explains the 12 principles.

European countries and groups in China and India have picked up the green chemistry idea (Nugent 2007; Kidwai 2001), but this analysis will focus on United States activities. Much of the early federal work in green chemistry policy occurred through the U.S. EPA. Paul Anastas was one of the first administrators to promote the idea through grants and other strategies. The EPA Office of Pollution Protection justifies its pursuit of green chemistry under the Pollution Prevention Act of 1990, which states source reduction, instead of effect remediation, as a priority: “pollution should be prevented or reduced at the source whenever feasible” (Public Law 101-508). This justification provides an early, codified public value that aligns with the goals of green chemistry. Currently, the most visible aspect of national green chemistry policy is the President’s Green Chemistry Award Challenges, which the EPA has awarded since 1996 to new advancements in chemical “design, manufacture, and use,” and goes to developments that “have been or can be utilized by industry” for pollution prevention.

One of the awards frequently cited by interviewees was a 1997 winner. The BHC Company won for developing a new process for synthesizing ibuprofen, which recycles the waste (such as acetic acid and hydrogen fluoride) from manufacturing the drug, and reduces 99% of aqueous salt waste. This results in a product that utilizes 99% of the atoms that go into production of ibuprofen, replacing a process that was 40% efficient. This type of process waste reduction, which enhances safety and environmental health, is exemplary of award challenge winners.

More recently, the 2008 President’s Award winners included a Greener Synthetic Pathways Award, which went to Battelle for developing a soy-based printer/copier toner. Batelle won the award because the process avoids using a petroleum-based material, facilitates toner recycling, and reduces energy use from both toner production and paper recycling. In the same year, the EPA awarded the Greener Reaction Conditions Award to a new technology for monitoring the chemical levels in industrial coolant water, thus reducing their use, and a Small Business Award to SiGNa Chemistry for their encapsulation of alkali metals in porous powders for safer transport and use.

Within federal research agencies, however, green chemistry still has a fairly low profile, with the EPA being the only one that takes a large role in its promotion. The National Science Foundation (NSF) does not have a green chemistry funding program, but does support a NSF Science and Technology Center for Environmentally Responsible Solvents and Processes. Most other agencies do not have formal ties to the field.

The non-governmental actors in green chemistry represent a mix of academic, for-profit, and non-profit concerns. Included among these is the ACS GCI. The main concern of the GCI is to promote the growth of green chemistry as part of the larger field of chemistry.[9] GCI also might represent some movement of green chemistry

[9] http://portal.acs.org:80/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_TRANSITIONMAIN&node_id=1400&use_sec=false&sec_url_var=region1&__uuid=c4aacda6-c527-4e7e-8c69-63dcdbb382d1 last accessed on 05/09.

towards mainstream acceptance; the institute used to be an independent non-profit organization, and is now part of the ACS.

Due to the large size of the industries involved in chemical production and use, increases in the efficiency and safety of one process or product can have enormous impacts. Products like ibuprofen sit in every grocery store and pharmacy in the country, so the advances such as those made by the BHC Company can greatly decrease waste when widely adopted. Green chemists claim that adding that waste reduction to the cost-effectiveness in improving such widespread industrial processes shows how green chemistry advances can have large impacts on commercial chemistry. At this time, groups are exploring means for expanding and influencing the role of green chemistry in industrial applications.

The Green Chemistry and Commerce Council (GC3) exists as a means for industrial participants, ranging from retailers like REI and Nike to pharmaceutical companies such as Pfizer, and large chemical companies like Dow, to push green chemistry's values. Although participation in GC3 obviously does not mean that an entire company is devoted to implementing green chemistry, it does imply that groups within the companies are working to use green chemistry as a means for increasing social and environmental responsibility, and thus have a "common interest in safer products" (Tickner 2009). The 77 industrial participants, under the coordination of the Lowell Center for Sustainable Production, participate by sharing information and promoting the green chemistry idea to the federal government and industry. Many of the members—especially those that began the GC3—are industrial chemical users, like REI and Patagonia, rather than producers. Although these companies cannot directly change chemical practices, they have the ability "to apply pressure upstream, to chemical producers" by demanding products created through green chemistry processes (Tickner 2009).

The GCI started another industry group, the ACS GCI pharmaceutical roundtable, for which the membership includes nine large companies, including Pfizer, Merck, GlaxoSmithKline, and Johnson & Johnson. The roundtable's goals include "integration of green chemistry and green engineering into the business of drug discovery and production."[10] According to the roundtable, "This collaboration results in a strong organization to prioritize research needs and influence research agendas, to interact with federal and international agencies and organizations, and to improve cost effectiveness of investment in the design and implementation of green chemistry and engineering tools specific to the industry." The roundtable has been growing in membership, from three companies in 2005 to nine in 2008. Its work has included funding research—a total of almost $500,000 to date—disseminating information on less hazardous reagents and solvents, and promoting green chemistry to policy-makers (GCI 2009).

A few states are also beginning to implement green chemistry or related ideas. Michigan Governor Jennifer Granholm, in a 2006 executive directive, ordered the State Department on Environmental Quality to promote green chemistry, citing the 12 principles under its definition of green chemistry (Mich ED No. 2006-06). This is

[10] http://portal.acs.org:80/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_ARTICLEMAIN&node_id=1424&use_sec=false&__uuid=6d3e8ddf-a8fa-4956-ba13-e60562bd2212 last accessed 5/09.

another example of the community values for green chemistry finding purchase and emerging as public values, at least for Michigan. In 2008, California enacted a statewide green chemistry program. Two bills (AB 1879 and SB 509) establish a process for identifying hazardous chemicals and authorizing one state agency to examine alternative chemical solutions. Depending on one's viewpoint and how implementation occurs, this could be either an adaptation or a cooption of the term 'green chemistry,' since it is currently unclear how this legislation will alter the development and production of new chemicals.

Green chemistry has also begun to see some growth in the traditional academic venues, including journals (*Green Chemistry*, since 1999), a Gordon Research Conference on Green Chemistry that has existed since 1998, and the annual Green Chemistry and Engineering Conference, which is in its 13th year. Additionally, there have been formal green chemistry education programs instituted in several colleges and universities, either as part of an existing chemistry program, or as interdisciplinary programs that combine chemistry and chemical engineering teaching with other disciplines, such as toxicology or environmental health. According to the American Chemical Society, 15 U.S. schools have Green Chemistry Programs.[11]

In the near future, green chemistry will likely continue to be a small but growing part of the chemistry enterprise and in academia. If successful, the Green Chemistry Research and Development Act would call for funding for green chemistry activities within NSF, DOE, NIST, and EPA. But even if appropriators funded the bill fully, the amount of funding, at $165 million dollars, is minuscule compared to the total chemistry budgets of these agencies. As written, the GCRDA does promise to have impact outside of research. It calls for an Interagency Working Group including NSF, NIST, DOE, and the EPA, and stipulates cooperation of efforts at NIST with small manufacturers, along with NSF funding for undergraduate green chemistry engineering. However, the prospects for the bill remain uncertain. The bill passed in the House of Representatives in 2007. In the Senate, Olympia Snowe and 7-co-sponsors introduced the bill (S. 2669), which was referred to the Committee on Commerce, Science, & Transportation, and not acted upon.

Green chemistry may also benefit from the recent posting of Paul Anastas as head of the EPA Office of Research & Development (ORD).[12] As leader of the office, Anastas has influence over the $541 million (2009 Budget) (AAAS 2008) agency R&D budget. Since green chemistry is primarily about changing research prioritization and implementation, this could be a positive development for the growth of the field. When talking about ORD grants under his leadership, Anastas said "it will be considered a baseline that green chemistry and engineering will be an integral component of submissions" (Baum 2010).

[11] http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_SUPERARTICLE&node_id=1440&use_sec=false&sec_url_var=region1&__uuid=a9b1348d-ade8-418a-8540-d986043581c5 last accessed 11/10.

[12] http://blogs.sciencemag.org/scienceinsider/2009/05/green-chemist-n.html last accessed 5/09.

Certainly the green chemistry community has ambitious goals. One 1998 workshop, including several leaders in the field, set targets to "reduce waste from polymerization processes by 30–40% by 2020," and to "totally convert solvent-based and water-based processes to 'green' processes by 2020" (NETI 1998, p. 5)

Educationally, the goal of leaders within the field is not to create distinct green chemistry departments in universities. Instead, John Warner has stressed that toxicology should be part of the chemistry education curriculum, since most chemistry students do not learn about the safety and environmental implications of the chemicals they work with (Warner 2008). This would be a step towards enabling future chemists to think through the sustainability implications of their work. It may also illuminate another distinction between green chemistry and traditional chemistry. While science values support chemistry education as a component of knowledge enhancement, green chemistry adds the instrumental value of education as a means for empowering chemists to integrate other public values into their work. Thus, knowledge and education are a goal unto themselves and a means to achieving other value goals.

Significant barriers also present challenges for green chemistry's advocates. One project on implementing green chemistry categorized future barriers to the field's growth in six groups including, "economic, regulatory, technical, organizational, cultural, and the definition of metrics" (Matus 2007, p. 2). The report also identified promotional strategies for overcoming these barriers, such as "consider policies to shift strategies to hazards reduction" and funding more research and education. While the feasibility of these strategies vary, and the potential for green chemistry to overcome such barriers is uncertain, the community is strategizing on how to proceed with further growth (Matus 2007).

Public Value Failure Assessment

Bozeman (2002, 2003) identifies criteria by which a public value failure can occur. When the criteria are not met, it represents a case where core public values are not reflected (Bozeman and Sarewitz 2005, p. 123). Bozeman (2002) proposed a first set of six criteria, including inadequate values articulation, imperfect monopolies, scarcity of providers, short time horizons, non-substitutability of resources, and benefit hoarding. According to green chemistry advocates, traditional chemistry fails to incorporate consideration of the impacts and consequences of research and production. These two categories of public value failure describe, first, a system that fails in its values articulation and is "insufficient to ensure effective communication and processing of public values" (Bozeman and Sarewitz 2005, p. 124). Second, in failing to consider the long-term sustainability consequences for new chemicals and processes, chemists and those who fund chemistry, including companies and federal institutions, employ a "short-term time horizon is employed when a longer-term view shows that a set of actions is counter to public value" (Bozeman & Sarewitz, p. 124). Additionally, chemistry, as commonly practiced, may fail in a way related to issues of substitutability, which I will call "neglect of alternatives" (Table 3).

Table 3 Public value failure in mainstream chemistry

Failure	Definition	Example
Values articulation	Political processes and social cohesion insufficient to ensure effective communication and processing of public values (Bozeman & Sarewitz 2005).	Status quo instrumental values in chemistry (including science values) impede the public values attainments of research in the field.
Short time horizon	A short-term time horizon is employed when a longer-term view shows that a set of actions is counter to public value (Bozeman & Sarewitz 2005).	Traditional chemistry values fail to account for long-term concerns of sustainability.
Substitutability vs. conservation of effort	Despite the presence of alternatives that benefit public value, they have not been instituted due to inertia brought on by disciplinary ideology, existing regulatory and infrastructural issues, or funding mechanisms.	Traditional chemistry has not incorporated alternative instrumental values despite the many examples of alternatives that have worked.

Values Articulation

Green chemists argue that there are status quo instrumental values in chemistry that lead to non-sustainable activities, like the dependence on petroleum-based feedstocks. Such dependencies may be based on unarticulated values such as one on reducing short-term costs. Such failures of instrumental value enforce a de facto intrinsic value result of reduced health and increased pollution. In other words, the values articulated on behalf of conventional chemistry imply a way of doing things that, while meeting goals of effective production and monetary gain, fails to account for other necessary values. This incomplete values articulation can reinforce the instrumental practices that produce hazardous or polluting chemicals since they do not provide an impetus for considering such practices. Currently, the relationship between the existing instrumental values and the posited intrinsic values is closed. The way institutions teach and propagate carry forward a set of intrinsic values that implicitly expel instrumental value that may increase beginning-of-pipe effects on health and environment. If dangerous chemicals are effective in their intended near-term function, and can make money, they still fit within the traditional chemistry values articulation where the science values of the discipline drive the instrumental process.

Short Time Horizon

A short time horizon is mainly evident in chemistry's failure to incorporate issues such as environmental health and human health, where consequences may emerge long after the chemicals are actually produced. While chemistry might focus on long-term market value or science value, the combination of values articulation failures and the failure to extend such values contributes to failures in traditional chemistry. The dominance of environmental chemistry approaches that fix the short-term effects of pollution, rather than work within the research system to replace the chemical or production process, is evidence of this lack of long-term thinking.

Neglect of Alternatives

The "substitutability vs. conservation of energy" category of public value failure from Bozeman and Sarewitz (2005) examines the assumption that two resources are substitutable in the market. The failure occurs because, when one includes public value concerns, the assumed substitutability is found to be false. Thus, a values collective assumes that substitutability is possible, when it is not. An example provided by Bozeman and Sarewitz (2005) is the strategy of wetlands creation to replace natural wetlands that have been developed upon. The substitution has significant non-market costs associated with it because manufactured wetlands cannot provide the environmental services of a natural one. According to green chemistry, resources are more substitutable than more traditional approaches assume, and a search for alternatives could lead to values successes. The difference is that for wetlands, people are trading a natural wetland in one place for an artificial, less valuable one, somewhere else. But in green chemistry they are trading a bad chemical/process that already exists for a better one.

Green chemistry's main tenet is that there are substitutions for popular chemicals and chemical processes that can be made to benefit public value, but have not been instituted by due to inertia brought on by disciplinary ideology, existing regulatory and infrastructural issues, or funding mechanisms. Substitutability, or pursuit of alternatives, is a desired public value outcome, but is in opposition to an existing conservation of effort/ideology. The system for chemistry research and production often uses hazardous materials and feedstocks because of entrenched to scientific and market value structures that fail to consider alternatives. Michigan's executive directive, along with groups like the EPA Office for Pollution Prevention, are chiefly about attempting to find such alternatives where appropriate.

Public Values and Green Chemistry

Although chemistry research has contributed to reductions in sustainability through negative chemical impacts, the discipline has also played a positive role in many sustainability issues. For example, ozone depletion, a problem partly caused by chemistry, has largely been improved because of the development of hydrofluorocarbons and other alternatives. Also, much chemical research is also integral to the development of alternatives to traditional hydrocarbons. Alternatively to traditional chemistry, green chemistry works to alleviate the effects of chemicals before they are ever felt. Thus, it attempts to improve on the public values potential of traditional chemistry by working towards low impact chemicals with more foresight, thus circumventing the need to continually react and respond to new problems. Green chemists, in attempting to address the longer time frame and value articulation issues associated with production, posit a framing of chemistry research that could lead to fewer public value failures. This does not mean that green chemistry itself will be free of public value failures. One of the strengths of green chemistry is that the system focuses mainly on the production and development of chemicals. As an active step away from end of pipe solutions, green chemistry seeks to avoid harm, in the short, medium, or long-term, by providing alternatives that are available in the short-term. In other words, green chemists do not wait for the environmental or safety consequences of a chemical to become problematic; they try to work preventatively to head off any potential negative consequences by developing products that are inherently more benign. However, although green chemists can try to account for and reduce known long-term hazards with this approach, the principles themselves do not call for post-production monitoring, although such strategies would be easy to implement under green chemistry's framework.

Despite its potential as a means for alleviating the toxic consequences of chemistry research and production, it is possible that on its own, the scope of green chemistry is too limited in only examining the evident toxic impacts of new chemicals. Although they were developed before the term green chemistry existed, chlorofluorocarbons (CFCs) show how a green chemistry solution could fail to account for long-term effects. In the 1920s, CFCs began to replace toxic gases such as sulfur dioxide as refrigerants, and in many ways they were a perfect green chemistry solution. For over 50 years industry used Freon and similar CFC products because they were cheap, efficient, and much safer than previous refrigerants. Since green chemistry is primarily concerned with toxicity, CFCs would be much preferable to previous refrigerants, and since green chemistry does not necessarily focus on the systemic nature of problems, or stress interdisciplinary approaches to solving them, it probably would not identify or address the eventual ecological impacts of CFCs (i.e. destruction of stratospheric ozone). This is not to suggest that green chemistry does not pursue a more diverse array of public values than does conventional chemistry. Few suggested switching back to sulfur dioxide refrigerants when CFCs' ozone-depleting characteristics were identified. Yet, the field would benefit from inclusion of more holistic problem solving and impact assessment, which might include the integration of expertise from other disciplines and procedures, like post-production monitoring of chemical effects might provide.

Green chemistry can never be universally useful, especially in the short-term. There are dangerous but essential chemicals that are irreplaceable with our current knowledge, or that replacement is too cost prohibitive even if non-economic gains can be made. However, green chemistry does have the potential to ameliorate the negative impacts of chemistry. A green chemistry approach by itself might have resulted in CFC use and ozone depletion. However, by focusing on the shortfalls of existing technologies and on sociotechnological solutions for them, green chemistry techniques could find appropriate replacements for many deleterious technologies. When performed with a use in mind, through consultation with or knowledge of an end user that is currently utilizing unsustainable chemistry compounds, replacing "normal" chemistry with green chemistry could offer sustainability advances without sacrificing economy. A group like the GC3, which is attempting to promote green chemistry with the cooperation and economic leverage of technologies' potential users, is one example of an organization that could push toward favorable developments.

Market Values Assessment

Chemistry, as scientists and corporations have practiced it for the last century, has been an indisputable market success, providing financial benefit and contributing to U.S. gross domestic product. ACS, in its promotion, stresses "the importance of chemistry in our lives. This includes identifying new solutions, improving public health, protecting the environment and contributing to the economy."[13] Despite its public values failures, mainstream chemistry has led to quality of life enhancements, life-prolonging medicines, and other values gains.

Green chemistry represents an attempt to add to the public values gains of traditional chemistry without detracting from its market successes. One of the advantages the field has is that proponents are not seeking to regulate away harmful chemicals, or to incur costs for industry. Instead, they seek benign replacements where it is economically and operationally feasible. While a widespread adoption of green chemistry is untested in terms of market success, there are signs that green chemistry research, when successful, can lead to market gains. The list of Presidential Green Chemistry Award winners and nominees provide many examples of green chemistry products that can also be market successes. Of course, these products may not have all been begun as intentional "green chemistry" research projects, but the outcomes still represent public values successes aligned with the 12 principles of green chemistry. Concentrated effort in green chemistry would seem very likely to produce new successes, such as the new, more efficient process for making ibuprofen.

Green chemistry typically produces less wasteful process with the potential for fewer end-of-pipe regulatory costs. The Presidential Green Chemistry Challenge gives evidence of past market successes. Together, these provide a strong argument for green chemistry being a market success of the same magnitude as traditional chemistry, with higher associated public value. Thus, a conceptualization of the relationship between the two might look like Fig. 1.

Value Chain Analysis

One remarkable aspect of green chemistry is the consistency with which proponents adhere to the values that Anastas and Warner lay out in their 12 Principles of Green Chemistry. Besides the scientists that explicitly follow the research processes laid out in the principles, many more policy oriented groups advocate for values structures that are consistent with the intrinsic values of the 12 principles, and often explicitly recommend adherence to the 12 principles. While not unanimous, this consistency does extend to the instrumental values as well. Environmental sustainability, public health, and reduced pollution are obviously not ideas unique to green chemistry. However, the green chemistry message depends on finding

[13] http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_TRANSITIONMAIN&node_id=225&use_sec=false&sec_url_var=region1&__uuid=9a8d62c5-9bb0-4112-8743-061666d0d417 last accessed 11/2010.

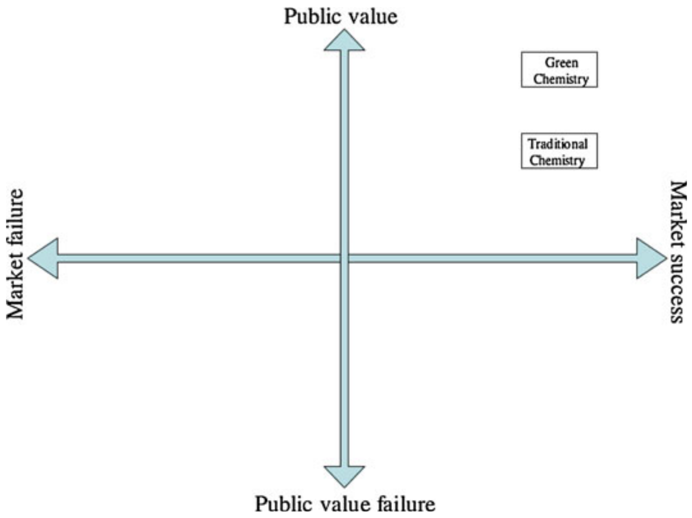

Fig. 1 Public value and market value for green chemistry and chemistry

substitute chemicals and "beginning-of-pipe" alternatives that differ from alternative strategies for reducing the impacts of chemicals, such as regulation, litigation, consumer awareness, or screening processes. As it now stands, green chemistry, as a small, cohesive field, represents a values chain that links instrumental values and intrinsic values with logical coherence absent from the broader chemistry field. One set of instrumental values, including work with non-petroleum feedstocks, the idea of atom economy, and utilizing non-hazardous materials, leads to the advancement of the green chemistry intrinsic values.

The consistency of the green chemistry values set may, to some extent, reflect the current small size of the endeavor. Worries about appropriation and cooptation of the term already exist (e.g. Woodhouse 2003; Tickner 2009). Influential policies in green chemistry do, to some extent, have the potential to maintain definitional integrity. For example, the Presidential Green Chemistry Award maintains the guidelines of the 12 principles as criteria for award winners. However, academic programs, companies, and policy-making bodies have the power to label programs as green chemistry, and some may end up doing so without the 12 principles as guideline. Although the current intrinsic groups in green chemistry could maintain consistency, growth of the field could obscure the definition, thus making the term more malleable, and perhaps less effective in representing one set of instrumental and intrinsic values. However, as it currently exists, green chemistry represents a value set, where the instrumental values, if utilized, define a chemistry research agenda that coherently allows for the inclusion of science values, but leads to the successful achievement of all stated intrinsic values.

Mainstream chemistry, if taken as a whole, represents the other end of this spectrum. Even though some groups within the field have long asserted public values such as quality of life, environmental health, and human health, there is a logical breakdown between the science, some of the instrumental values, and these asserted intrinsic values. Thus, the instrumental values that enable the research do not generally include health, atom economy, or the production of safe byproducts. While the eventual chemical output could potentially meet a health need, as ibuprofen does, the process that contributes to the product can still contribute hazardous materials, until the intervention of green chemistry refines such processes.

Furthermore, the intrinsic value set is more limited in conventional chemistry; sustainability concerns are not universal. Values agreements across chemistry, whether in textbooks or industry groups, tend to focus on production, quality of life, and knowledge gains. These values articulations tend to be similar to science values claims, such as Vannevar Bush's expression that basic research can lead, almost automatically, to "health, well-being, and security" (Bush 1945). The means to the accomplishment of chemistry values are simply the pursuit of chemistry research, accompanied by the traditions and assumptions of the field as researchers have followed it in the 20th century. Although the function of the chemical product may differ widely depending on the sector and purpose, the chemistry methods, as formally laid out, and as implicitly accepted, do shape conduct of the field to a point where green chemistry's argument for alternatives is a valid one since conventional chemistry's neglect of public value-oriented instrumental value can lead to negative outcomes. Since chemistry has been able to succeed in the realm of market values simply through use of science values, chemists and policy-makers have neglected other public values. So, even when there is a coherent value chain where the instrumental values encompass the intrinsic values, some endeavors may miss the public values addressed by green chemistry.

John Warner stipulated that, although the chemistry industry must concern itself with market values, chemists, and especially university chemists, do not share market concerns. Conformance to process-oriented, instrumental values such as the scientific method, knowledge, and expert-driven inquiry, is not detrimental in itself, but as practiced, have led to a status quo for which the outputs are often effective, but also occasionally hazardous. The major reason not to consider the methods proposed by green chemistry would be if the results of the process were fruitless or less effective. If alternatives to existing hazardous methods could not bear fruit, green chemistry's argument is moot. However, the many successes of the field point to the likelihood that there are gains to be made by growth of the field.

Recommendations

Continued growth of green chemistry may require federal funding of research, and more formal incorporation into academic programs. The Green Chemistry Research & Development Act, with its modest budget, could be seen as a sort of model for how the field could work. A limited research budget might enable agencies to support research programs, without growing green chemistry efforts too far beyond their current capacities, or reducing the efficacy and prominence of traditional chemistry efforts. A successful GCRDA could prove to be a useful jumping off point for expanded federal efforts in green chemistry, which could then have more impact on public value goals. Outside of the GCRDA, agencies could move projects towards more sustainability-oriented practices. The idea of sustainability, and encouraging sustainable production, is one that is a growing concern in both industry and government.

Outside of federal policy, institutionalization of green chemistry priorities in academic programs would help chemists make informed decisions about the impact of their work. Policies similar to John Warner's proposal that chemistry programs incorporate courses in toxicology would allow chemists to maintain the disciplinary skill set necessary to follow a career in chemistry research, while increasing their ability to consider hazards in their work, and opening them up to the opportunities of green chemistry.

Green chemistry aims to reduce the long-term impacts of chemicals. Perhaps because Anastas and Warner direct their 12 principles at chemistry researchers, they do not address the possibility for long-term monitoring of new green chemistry products and processes. Although the likelihood for green chemical products to have negative effects is already reduced by the principles, unforeseen risks could affect future hazards. While some in the community have proposed predictive approaches, including modeling and life cycle analysis (NETI 1998), to assess the future impacts of chemical products, this still leaves room for unanticipated consequences. Thus, some monitoring may be necessary, especially for chemicals that find widespread application.

These steps along with continued growth in industrial interest and the overcoming of other barriers, such as regulatory ones (e.g. many environmental regulations focus on exposure instead of hazard reduction, and unwieldy drug recertification process impede the altering drug production systems) (Matus 2007), could lead to a growth in green chemistry research and, assuming continued successes in the outcomes of such research, an increased achievement of the sustainability goals that those in the field subscribe to. As more people train in green chemistry's outlook and practices, the enhancement of a sustainability agenda, and a public values agenda, may become more likely.

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