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Green chemistry and Green Engineering in China: Drivers, Policies and Barriers to Innovation

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Abstract

With the world's largest population and consistently rapid rates of economic growth, China faces a choice of whether it will move towards a more sustainable development trajectory. This paper identifies the different factors driving innovation in the fields of green chemistry and green engineering in China, which we find to be largely driven by energy efficiency policy, increasingly strict enforcement of pollution regulations, and national attention to cleaner production concepts, such as "circular economy." We also identify seven key barriers to the development and implementation of green chemistry and engineering in China. They are (1) competition between economic growth and environmental agendas, (2) regulatory and bureaucratic barriers (3) availability of research funding, (4) technical barriers, (5) workforce training, (6) industrial engineering capacity and (7) economic and financial barriers. Our analysis reveals that the most crucial barriers to green chemistry and engineering innovations in China appear to be those that arise from competing priorities of economic growth and

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environmental protection as well as the technical challenges that arise from possessing a smaller base of experienced human capital. We find that there is a great deal of potential for both the development of the underlying science, as well as its implementation throughout the chemical enterprise, especially if investment occurs before problems of technological lock-in and sunk costs emerge.

Keywords:

green chemistry, innovation, sustainable development, China, circular economy

1.1 Introduction

Throughout its history, chemical innovations have made crucial contributions to improving the quality of life for people all over the world. In China, and throughout the world, the chemical industry has been an important part of innovations that led to life-saving medicines, fertilizers that have helped alleviate hunger, and microprocessors that have revolutionized computing and communications (Arora et al., 1998). All of these have contributed to helping to improve the lives of hundreds of millions of Chinese. Unfortunately, in China, as in many other developing countries, a focus by industry and government on increasing growth, ramping up development, and continued expansion has resulted in significant harm to the environment and local population s(Liu and Diamond, 2005; WorldBank, 2007). So while the chemical industry has been a major contributor to improving the quality of life, it has also been a source of harm. This pattern is not unique to the chemical industry, or to China, and is part of a larger, historical pattern of development to improve livelihoods that has come at a high price to human health and the environment. To be sustainable in the future, China will need its chemical industry to operate according to a new paradigm, one that can enable growth without adversely impacting society and the environment.

Green chemistry and green engineering, much like the wider concepts of sustainability science, help to balance the need to improve quality of life while maintaining the health of humans and the environment. Green chemistry and green engineering are a way to use scientific knowledge to reconcile a very real need for chemical production and use with the desire to reduce the hazards -- global, physical, and toxicological-- associated with these activities. Green chemistry is the "design of products and processes that reduce or eliminate the use and generation of hazardous substances (Anastas and Warner 1998, 30)." Green chemistry and its sister discipline of green engineering (Abraham and Nguyen, 2003; Anastas and Zimmerman, 2003) provide innovative answers to questions about how we can deploy scientific and engineering understanding to challenging and complex sustainability problems that have emerged as the result of technological advances. While green chemistry and green engineering are themselves part of the scientific basis forming solutions for sustainable development, they also necessarily interact quite strongly with the realm of policy. Creating, producing and using chemicals sustainably require innovative activity, economic investment, and policies that provide positive incentives to reduce hazards. All of these actions involve a variety of stakeholders from academia, industry, government, and the general public. As such, the future success of green chemistry and green engineering as real-world tools, and not just academic disciplines, depends on more than just excellent science. It also requires actions by other stakeholders to move innovative solutions from the laboratory to systematic implementation throughout the chemical enterprise.

For China, as for other countries, it is a complex and challenging process to move from the understanding that green chemistry and green engineering are important tools for addressing conflicts between economic growth and the environment, to the point where their implementation is systematic and effective. China, with its rapid growth and investment in new capital infrastructure in the chemical industry, has a unique opportunity to implement new, more efficient technologies with fewer negative environmental impacts. However, there is no indication that this is the path being chosen for the majority of projects. The science of green chemistry and green engineering has emerged as a way to reconcile a very real need for chemical production and use with the desire to reduce the hazards -- global, physical, and toxicological-- associated with activities in the chemical enterprise.

China has been making progress in a number of green technologies and is continuing its efforts to grow green chemistry and green engineering (Cui, Beach, and Anastas 2011). But in China, the dynamics of moving beyond an understanding that green chemistry and green engineering are important tools for addressing the conflicts between economic growth, environment, and towards a systematic and effective implementation remains a complicated and challenging process. Innovators face a variety of challenges and barriers that make it difficult to integrate green chemistry and green engineering in a systematic and effective manner, despite the potential for economic, environmental and health benefits. This paper will analyze the current state of green chemistry and green engineering in China, including the different drivers, challenges, and policy approaches that are currently present, in order to aid in the future development of green chemistry and green engineering in China.

This analysis is based on material collected during interviews conducted in China between 2005 and 2011. All of the interviews were qualitative, and semi-structured, based on a common interview protocol. This kind of qualitative interviewing process is conversational by nature, and as such, the focus and order of the topics covered differed from interview to interview. It is based on a set of topics to be considered, as opposed to a more formal set of survey questions[f] (Babbie, 2007). Subjects agreed to be interviewed under an agreement that their responses would be kept confidential[g]. The interviews took place at twelve research universities and institutes throughout the country, and additional information was collected through attendance at several conferences, meetings and industrial site visits dealing with green chemistry and green engineering, green energy, and sustainable development in China[h],[i]. The sample consisted mainly of academic institutions involved in collaborative efforts with industrial partners, in order to determine barriers throughout the innovation process, from laboratory research through production. The academic institutions in the sample are all on the East Coast, in relatively prosperous and industrially developed regions, and are also some of the leading science and engineering research universities in the country. For this reason, they are likely to be

[f] See Appendix for Interview protocol

[g] Information specific particular interviews are paraphrased, and cited based on title, affiliation, and date of interview in order to protect the subjects.

[h] **Universities, industries and local governments Visited in China**

Beijing University of Technology; Beijing University of Chemical Technology; COFCO's 200,000 tonnes cassava fuel ethanol project in Beihai City, Guangxi; Guangxi Academy of Sciences; Guangxi Government; City government of Beihai, Guangxi Province; Institute of Chemistry, Chinese Academy of Sciences; Institute of Process Engineering, Chinese Academy of Sciences; Nanjing University of Technology; Natural Science Foundation of China; Shanghai Jiao Tong University; Sichuan University; Southern China University of Technology; Tianjin University; Tsinghua University; University of Science and Technology of China; Zhejiang University;

[i] **Workshops and Conferences**

China-U.S. Center for Sustainable Development, Board Meeting, June 2006, Beijing
8th Annual International Symposium on Green chemistry and green engineering in China, June, 2007, Beijing*
1st Asia-Pacific Conference on Ionic Liquids & 1st China National Conference on Ionic Liquids and Green Processes, November 2008, Beijing*
Industrial Site visit for biofuel development in Guangxi, China from November 18-23, organized by 1st U.S.-China Green Energy Forum, November 16-18, 2008, Beijing

Guangxi Academy of Sciences Workshop on Biofuels in Guangxi, November 22, 2008, Nanning*
International Conference on Clean Energy Science, Dalian, China, April 10-12, 2011

among the cutting edge in terms of adoption, but are also influential and well-respected in the academic science and engineering community. But they do not represent the full range of Chinese academia. The Chinese academic green chemistry and green engineering community was highly supportive. Many of the participants have engaged in extensive work with industry, and thus had insight into the factors that impacted green chemistry and green engineering in that sector as well. All of those interviewed had prior knowledge of the area, although there was variation in how long their work had involved green chemistry and green engineering as a major component.

2.1 Trends, Policies and Drivers

Green chemistry and green engineering have grown rapidly within the scientific community in China. The first International Workshop on Green Chemistry was held in 1998 (Hjeresen et al., 2001; Woodhouse and Breyman, 2005). The first China-USA Green Chemistry workshop took place in 2005 (R.D. Rogers, 2006). It was attended by a small number of scientists, many of whom did not yet work on areas that would be considered green chemistry and green engineering. In the ensuing decade, research and practice significantly expanded. For example, in 2001 the Institute of Chemical Metallurgy at the Chinese Academy of Science was renamed the Institute of Process Engineering, and its research was specifically redirected to greener chemical processes innovation (Ng et al., 2005). This resulted in the commercialization of a clean production method for chromic oxide in 2002, one of the first industrialized green chemistry projects in China (Zhang et al., 2008).

Other national initiatives followed, including the National Program for Experimental Units of Circular Economy. This initiative, begun in 2005, addresses concepts that have significant overlap with the Twelve Principles of Green chemistry (Anastas and Warner 1998), including zero emissions, clean production, low resource utilization and high energy efficiency (Yong, 2007). While circular economy does not have a single definition, it generally stresses closed flows of materials, and increased efficiency in the use of raw materials and energy (Park et al., 2010). As of 2008, the program had been extended to 11 provinces, 16 cities, 33 circular industry parks and 120 companies (Department of Resource Conservation and Environmental Protection of China National Development and Reform Commission, 2005, 2007). At the First China International Cyclic Economy Exhibition in Qingdao in 2008, more than 1200 firms, 31 provinces, and 150 cities and areas in China, along with international corporations, attended to share their products, progress achieved, or their need for a local Circular Economy.

The development of green chemistry and green engineering also progressed during this period, and at the 9th International Workshop on Green Chemistry in 2007, several hundred students, professors, members of the industrial community and officials were in attendance. They represented more than a dozen research centers around China explicitly focused on green chemistry and green engineering, and numerous other research groups and firms engaged in green chemistry and green engineering in a wide variety of sectors.

Interviews with academics involved in green chemistry and green engineering research helped to identify many of the important trends and features involved with green chemistry innovation in China. A summary of these is presented in Table 1, which shows how many interviewees discussed five particular topics during their interviews. These topics were the five most commonly mentioned, and are discussed in greater detail later in this section. It is important to note, however, that given the nature of the qualitative interview, the fact that a certain drivers or barriers were not mentioned during the course of an interview does not necessarily indicate a divergent opinion. In fact, there was almost no overt divergence of views on these topics. Instead, the variation appears to be on which trends and issues are considered the most important by each individual academic.

Trend and/or Feature of Green Chemistry and Green Engineering Research	**Number of Academics Reporting (N=12)**
Academics Personally Engage in Research with Industry	10
Research and Funding Driven by Regulatory Trends (i.e. energy efficiency, increased enforcement)	7
Graduate Students Do Research in Industrial Settings	6
Joint Government-Industry Funding Programs	5
Funding for Green Chemistry Improving	3

Table 1- Trends and Features of Green Chemistry and Green Engineering Research Identified by Academics

As inspection of Table 1 reveals, the key insights that came from academics were focused on how research is supported, in terms of financial backing, as well as which partners are involved. The growth of green chemistry and green engineering has been actively and widely supported by both industry and the government. For example, in the Institute for Process Engineering, less than 40% of its funding is from its parent organization The Chinese Academy of Sciences (CAS), with the remainder coming from other government departments, such as the China Ministry of Science and Technology (MOST), the China National Development and Reform Commission (NDRC) and local governments, industries, agencies and sources outside the CAS through more competitive processes. This 4:6 ratio of internal to external funding is required by CAS for all of its institutes engaged in technology and engineering (Chinese Academy of Sciences, 2010). The percentage from industry is estimated at about 40% of the total funding obtained from both inside and outside, and is a little bit higher than the average level of industrial support for academic research in China, which is 35% (National Science Board, 2010). At the National Natural Science Foundation of China, 20-25% of basic research funding in chemical engineering goes towards green chemistry and green engineering projects, and the percentages are the same or greater within organic and physical chemistry[j] (Official, National Natural Science Foundation China, Beijing, 2008; Professor, Beijing University of Technology, 2008). Both the NSFC and the researchers in the field define green chemistry according to the "12 Principles of Green Chemistry." Such strong connections between academics and industry provide a pathway that allows research to move from the laboratory to commercialization.

There are currently several drivers in place in China that have helped expand the implementation of green chemistry and green engineering research. There has been a large increase in public awareness of environmental issues generally, and about safety and health risks from chemicals in particular. A number of scares involving tainted products (including pet food, infant formula, and toothpaste) and chemical releases into major water sources in 2005, 2009 and 2010 (Anon., 2005; Karmanau, 2005; Meyer, 2008; Bodeen, 2010) have increased the concern among the public regarding the chemical industry in particular. Professors report that university students have an increasing awareness of green issues. As China becomes an important participant in green technologies, demand is growing for the scientific and engineering training required in these emerging fields. Green chemistry and green engineering courses are taught at a variety of levels, including for undergraduates and non-majors, at more than a dozen major Chinese universities. The first generation of these courses were geared towards master's students, but courses have been expanding to other levels at the university level, and several academics reported that their popularity has been increasing in recent years (Professor, CAS Institute of Chemistry, Beijing, 2007; Professor, Tianjin University, 2007, 2008).

[j] Estimated according to the report on the Chinese NSFC grants at http://kyc.gdcc.edu.cn/xzzq/2007xz/gjzrjjsbpx.ppt (accessed February 4, 2010) and discussions with professors and officials involved with the Chemical Engineering grant awards process.

It appears that most of the regulatory drivers of green chemistry and green engineering are indirect. In terms of drivers that come from the regulation of chemicals, the regulatory system in China is relatively new. Regulation of imports and exports of toxic chemicals began in 1994; regulation of new chemicals in 2003. China is also a signatory on two important international treaties, the Rotterdam Convention (pesticides and hazardous chemicals) and the Stockholm Convention (persistent organic pollutants) (Wang et al., n.d.). A 2007 report by the China Council for International Cooperation on Environment and Development concluded that "management of chemicals in China is weak" and went on to list five fundamental flaws: a lack of clear national policy, absences of a system of laws and regulations, inadequate administrative, enforcement and supervision capacity, insufficient public participation, and absences of technical support system for administrative management (Hu Jianxin, 2007). Responsibility for chemical regulation has been split between a number of ministries, and it was only in 2009 that a body for chemical management was established in the Ministry of Environmental Protection (MEP). The MEP now has the authority to regulate a priority chemical list, and released its first 5 year plan for chemical management at the end of 2011. Its focus, however, is on encouraging reporting and the collection of data. More formal control measures would require the involvement of other industrial ministries, making them harder to implement (Campaigner on Toxics, Greenpeace China, Beijing, 2012). Overall, chemicals policy is in a period of change, and a stronger regulatory framework is emerging. But it does yet cover the entire lifecycle of chemicals (Wang et al., n.d.), and is nowhere near as developed as TSCA in the United States, or REACH in the EU. This is significant because recent research from the OECD indicates that meeting mandatory regulatory requirements is the most important policy driver behind firms' decisions to invest in research, development and deployment of green chemistry innovations.

Given its weaknesses, domestic chemical management policy has not yet played a role as a major driver for green chemistry and green engineering in China.

The absence of a strong influence from the regulation of chemicals does not mean that other large, national policies are not having an impact. Current Chinese energy policy is an important indirect policy driver. The 11th Five-Year Plan (2007-2011) was the first in Chinese history to include hard targets for reductions in energy consumption. In this case, the goal is to decrease the energy intensity of the economy 20% by 2011[k], and initial analyses indicate that the target was met or nearly so (Lewis, 2011; Price et al., 2011). The government further disaggregated the overall national target to each of the provinces, which in turn developed hard targets for local officials (National Development and Reform Commission (NDRC), 2006). While previous Five-Year plans contained language regarding environmental performance, this is the first time that there have been hard targets that officials are expected to attain. Since attainment of such goals has a direct impact on career advancement, this has the effect of focusing the attention of government at all levels on improving the energy efficiency of industry. These policies continue in the Twelfth Five Year Plan (2011-2015), which was announced in March, 2010. New targets included a 16% reduction in energy use per unit GDP, with more specific environmental targets forthcoming[l] (Seligson, 2011; Seligson and Hsu, 2011). At the very least, these will continue to drive green chemistry forward in a similar fashion as during the 2007-2011 period.

[k] Denominated in tons of coal per unit of GDP.

[l] Key targets of China's 12th five-year plan [WWW Document], 2011.URL http://news.xinhuanet.com/english2010/china/2011-03/05/c_13762230.htm

To meet such an aggressive target, government officials are working with industry and academia to pursue a variety of technological approaches to increase the efficiency of the economy. Green chemistry and green engineering fit in very well with this effort. Because of the energy efficiency targets, scientists and chemical firms are interested in moving towards pollution prevention methodologies and away from costly and energy-consuming end-of-pipe effluent treatment systems. Some of the work has been along the lines of process engineering improvements. There are also upstream projects underway, some of them jointly funded by industry, government and academia, in areas such as new solvent platforms, solid-state reactions, and catalysis (Professor #1, Southern China University of Technology, 2008; Professor, Tianjin University, 2008; Professor, Zhejiang University, 2008; Cui et al., 2011).

Over the past few years, there has been a trend towards increasing the direct support of green chemistry and green engineering by the Chinese government. While in the literature, the Chinese government is portrayed as only being indirectly involved in academic-industrial collaborations and commercialization (Chang and Shih, 2004; Eun et al., 2006), almost all of the interviews with professors around the country described a situation of active support. There are many examples of university-industry collaboration that demonstrate a significant government influence. This goes beyond the indirect involvement that arises when funding ministries set their budgets and decide which areas of research should take priority. In fact, government at a variety of levels is taking on the role of a third-party intermediary between academics and industry.

One example of direct government involvement comes from the case of the phase-out of carbon tetrachloride (CCl_4) during the production of methyl chloride. Carbon tetrachloride, in addition to being highly toxic, is also an ozone depleting substance. China, as part of the

Montreal Protocol, had agreed to its phase-out (Zhao and Ortolano, 2003). Using money from a fund established for this purpose by a multi-lateral fund of developed nations, the State Environmental Protection Agency (SEPA) funded work at the Beijing University of Chemical Technology (BUCT) to develop a new method for the production of methyl chloride, and then helped firms implement this new technology. Faculty and students from BUCT visited more than 300 sites in order to target their research to the needs of industry. The Chinese government also aided the process through a policy to shutter the smaller firms, leaving only larger firms with the ability to implement the new technology. The government provided money directly to industry, which came from the multilateral fund, to finance the technology change.[m] In this case, the government was active as a funding source, in that it was in charge of the distribution of the international funds, but also worked to catalyze cooperation between academia and industry that was required to both develop and implement an appropriate technology to address the problem.

A second method of government involvement in green chemistry and green engineering comes from efforts to create joint research centers. In these cases, governments at a variety of levels, ranging from the municipal to the national, have offered to put funds towards the creation of a particular center, provided that the university secures an industrial partner. For green chemistry and green engineering, the pattern appears to be that the government chooses a problem area of particular interest, and then sets up a competitive grant process. In this case, government, and not industry, sets the research priority. This has the advantage of having the potential to spur investment in more transformative, though potentially risky long-term research.

[m] Personal Communication, BUCTT, Beijing, China. November 28, 2007.

The third way that government is increasingly becoming involved in advancing green chemistry and green engineering is as a “matchmaker” between academia and industry. Firms can submit particular problems that they are willing to fund, such as efficiency improvements in a particular process or the replacement of a particularly toxic or environmentally intensive chemical input. If any research groups are interested in that particular project, they can submit a proposal. The top proposals are usually invited to present to government officials, who then decide who will receive the industrial “grant” (Doctoral Researcher, Nanjing University of Technology, 2008). This method helps to expand the network of expertise available to firms, who may gain access to research capabilities from a wider geographical range than was previously available. It also helps researchers to better assess what areas of work are particularly useful to industry. This is a new and developing system, and it has yet to be seen what its overall impact will be on increasing the widespread implementation of green chemistry, green engineering and other technologies for sustainable development.

For green chemistry and green engineering in China, there are economic incentives, as well as policy drivers pushing research, development and implementation forward. There are cases where collaborations between stakeholders were mandatory, such as the phase-out of CCl_4 in methyl chloride production. There are other examples where increased enforcement drives industry to look to academia for new prevention or abatement technologies. Policy demands also provide markets for new products that have been spun-out either in new enterprises or joint-ventures with industrial and academic involvement. And government priorities, especially for green energy and improved energy efficiency of existing production, have resulted in support for new green chemistry and green engineering research centers that include significant amounts of industrial funding (Official, National Natural Science Foundation China, Beijing, 2008; Professor, Tianjin University, 2008).

3.1 Barriers to Green chemistry and Green Engineering Innovations

China has a different context for green chemistry and green engineering innovations than nations in the developed world, such as the United States. It is growing rapidly, and this includes its academic research system, along with its industrial base. China is in the process of increasing the quantity and quality of its human capital. Simultaneously, it is dealing with the environmental impacts of three decades of rapid economic growth, which has often come at the expense of environmental quality (Economy, 2004). Especially compared to the United States, there is a large amount of investment in new capital infrastructure, which in principle provides opportunity for the implementation of new green chemistry and green engineering technologies. Within the Chinese context of a rapidly developing nation experiencing significant growth and change, innovators can face several different types of barriers during their attempts to develop and implement new technologies. In China, there are seven major categories of barriers that have been observed thus far that directly impact green chemistry and green engineering. They were identified based on the qualitative interviews, as supported by the published literature. They are (1) competition between economic growth and environmental agendas, (2) regulatory and bureaucratic barriers (3) availability of research funding, (4) technical barriers, (5) workforce training, (6) industrial engineering capacity and (7) economic and financial barriers. These barriers are discussed in detail below.

3.1.1 Barriers resulting from competing agendas

The clearest barrier to systematic green chemistry and green engineering implementation is the problem of competing agendas. Since 1978, China has focused nearly single-mindedly on its economic growth. It has achieved spectacular results, with GDP growth averaging nearly 10% between 1978 and 2007 (The World Bank Group, 2009) . For most of that era, the growth occurred without much thought regarding the environmental consequences. The environment and development were seen as competing agendas. That attitude is changing, especially during the 11th 5-year plan from 2007-2011, which includes specific targets for energy efficiency (20% increase in energy efficiency per unit GDP by 2011 (National Development and Reform Commission (NDRC), 2006)).

Even if the situation is changing with the environment becoming an explicit concern, there is still a great deal of local variation. In Jiangsu Province, in Southeastern China, there is an extensive system of remote monitoring, and severe penalties are incurred by firms whose waste emissions exceed authorized levels. This began in 2008, though a professor who has been involved with the provincial government in the province reports that there is a great deal of manipulation by local towns, and the results remain uncertain (Professor, Nanjing University of Technology, 2008; Van Rooij and Lo, 2010). This is still more advanced than the western provinces, where the main concern is still the large level of poverty, and development projects in these areas still have priority. Additionally, monitoring and enforcement standards are not as rigorous (Van Rooij and Lo, 2010).

While green chemistry and green engineering have the potential to benefit both the environmental and economic agendas, there needs to be more understanding within industry and academia of its economic benefits, not just its potential to reduce polluting emissions or increase energy efficiency. Otherwise, there is a risk that in times of economic trouble, it may be unwisely dismissed as an unaffordable luxury.

3.1.2 Regulatory and bureaucratic barriers

Green chemistry and green engineering implementation in China struggle with regulatory and bureaucratic barriers. First of all, there are no regulations in China that require the official accounting of toxic releases into the environment. Emissions regulations designed to protect water resources use measures such as chemical oxygen demand (COD), which is an indirect test for organic pollutants (Tremblay, 2010). COD levels, however, do not give information on different pollutants, such as mercury, other heavy metals, or PBT's. This means that the largest potential regulatory driver for these technologies is lacking (Environment Directorate, Organisation for Economic Cooperation and Development, 2011). Without a regulatory "floor" to set minimum levels of toxic releases, or even a method to track them, there is little regulatory incentive for firms to invest in many green chemical and green engineering technologies that reduce the use and emissions of non-organic pollutants, despite their known hazards. In addition to the lack of attention to certain kinds of toxic releases, there are also no regulations in place to create direct incentives for green chemistry and green engineering. While the government has supported funding of specific research and development projects, there is not, as yet, any broad Chinese green chemistry and green engineering policy in place, nor was it specifically mentioned in initial announcements of the 12th Five-Year Plan (Casey and Koleski, 2011; Seligson, 2011).

There are also challenges that emerge from the nature of bureaucracy and enforcement across China. Many of the most important decisions that affect growth and implementation occur on the local or provincial level. This means that officials at these levels need to be aware of green chemistry and green engineering and its potential benefits. They must also have the proper authority and incentives to support green chemistry and green engineering projects. This is a challenge not just for green chemistry and green engineering per se, but also for the underlying environmental regulations that can be important drivers. Because of the competing priorities facing any bureaucracy, environmental enforcement across China has been very uneven (Van Rooij and Lo, 2010). While some provinces have become stricter, others are considerably more lax. In regions with less stringent regulations, professors who work with industry describe situations where fines may be so small, and rarely applied, that they do not create incentives for change. For those firms in stricter areas, often the choice is to improve or to move. And for many, the choice to move may be cheaper, or less uncertain, than figuring out how to use approaches like green chemistry and green engineering to reduce or eliminate pollution. As enforcement improves, and there are fewer and fewer pollution havens, this will become less of a problem. But investment in green chemistry and green engineering will still require that local officials understand, and value it as an approach by enforcing stricter standards, while at the same time invest resources in projects that aid local chemical firms in developing and implementing green chemistry and green engineering technologies.

3.1.3 Funding for precompetitive research and development

Funding for green chemistry and green engineering would seem to be a universal challenge. But there are aspects to the funding problem in China that are different from the funding problem in the United States or the EU. In China, there is generally a smaller pool of available funds for research and development. While the Chinese National Natural Science Foundation's budget has been growing rapidly, in absolute terms, it still is less than 10% of what the United States government spends on research each year. Furthermore, Chinese industry in the past has not had the deep pockets to fund R&D to the level seen in the United States, Europe, and even other parts of Asia. This is changing, but even as China's R&D investment has seen unprecedented growth over the past decade (National Science Board, 2008), funding is still limited and highly competitive. In 2010, the funding rate for chemistry proposals was 23%, and for engineering was 18% (NSFC, 2010). In the same year, of sixteen 1 million CNY Major Project grants, only one went to a green chemistry project (NSFC, 2010).

This has two impacts for green chemistry and green engineering. The first is that the focus has been on the industrial applications of green chemistry and green engineering, as opposed to fundamental, basic research (the kind that results in new approaches and technologies later on across a variety of platforms). Application is obviously an important aspect, but since it rests on the existing body of scientific knowledge, moving that fundamental understanding forward is an important part of ensuring that green chemistry and green engineering can expand the areas in which it can be used, and can address future challenges. This is especially important for areas that may be important in the future in China, but not elsewhere. While there is nothing wrong with importing and adapting technologies from elsewhere where available, China has its own unique mix of industrial needs and constraints. From a long term perspective, it could be problematic to have underinvested in basic research required to address challenges that are particular to the Chinese context.

The relative difficulty in obtaining government funding for green chemistry and green engineering has had a second impact, which can be seen in Chinese engineering in general. According to several Chinese professors, for many years, Chinese firms did not have the money or the human capital to support permanent, internal R&D. If they ran into a technical problem, they would pay one of the research universities to solve it for them. This became an important source of research funding, to the point where many academic science engineering research centers were acting, at least in part, as contract research organizations. This system endows industry with a great deal of power to direct the academic research agenda. On the one hand, this can be seen as a positive, since there is a real benefit to closely linking academic research with industrial needs. But there are downsides. First, not all of the results of sponsored research could be published or patented by the researchers. And secondly, research agendas that are dominated by the current needs of industrial actors are reactive. This negates the advantage that science provides in being proactive. Today’s research may solve tomorrow’s problems.

Even as the research funding situation has changed, and firms are more able to engage in research partnerships and joint centers, the public and privately funded research agendas are industrially driven. This can provide excellent, useful incremental improvements. The problem is that there is not funding for the kind of transformative research that is required to tackle the big problems of sustainable development. Green chemistry and green engineering have the potential to enable radical changes, not just marginal improvements. But that requires industry, the government, or both to invest in long-term research projects whose use and economic return is not immediately known.

3.1.4 Technical barriers

Technical barriers to the implementation of green chemistry and green engineering exist everywhere, and some of China’s challenges are not uncommon. But there is a need to innovate, adapt, and in some cases, to invent green chemistry and green engineering technologies that can explicitly address the particular problems faced in China. The growth in the development of green chemistry and green engineering in China is not enough to address the overall need, and the research as a whole is still in early stages compared to that in the U.S., the EU, and some other countries in Asia. Many of the sustainable solutions to the problems faced by Chinese chemical producers and users have not yet been invented either domestically or abroad (Cannon and Warner, 2011), so that even those that would like to use a green chemical solution might not be able to do so.

Another nuance to the technical problem in China is the availability of green chemistry and green engineering technologies that are developed elsewhere. Concerns about intellectual property protection prevent many firms from selling or licensing green technologies to Chinese firms (Sims-Gallagher, 2006). Domestic Chinese chemical firms may not have access to green chemistry and green engineering solutions that are available to foreign competitors. Even when they are able to access these technologies, they must be adapted to local contexts. This takes time and investment, as well as technical expertise on the part of the firms that are importing solutions. Several research centers at Chinese universities have formed partnerships with foreign firms in order to adapt green chemistry and green engineering technologies which they can provide for use by Chinese firms. Tianjin University, for example, has partnered with Sud-Chemie, Englehart and BASF on catalysis research (Professor, Tianjin University, 2008).

3.1.5 Training

Related to the technical challenge is the barrier that occurs when the scientists and engineers who are needed to develop and implement green chemistry and green engineering do not have the necessary background and training. The availability of green chemistry and green engineering coursework in Chinese universities is growing, but there are only a handful of faculty who possess the necessary background to teach green chemistry and green engineering at all levels. This limits the penetration of the subject into core chemistry and engineering curriculums, even as interest grows. Furthermore, those courses that do exist are usually electives. Scarcity and the elective nature means that the vast majority of scientists and engineers in the workforce have not been exposed to its principles. One professor reported that despite the existence of green chemistry courses available for the chemical engineering graduate students, almost all of his students learned about green chemistry when they joined his research group (Professor, Zhejiang University, 2008). Also, it is not just the engineers who operate technologies, or who work in industrial R&D that are needed for the implementation of green chemistry and green engineering. It also requires managers who are aware of the value of green chemistry and green engineering to their enterprise, and who are savvy enough to understand how it can best be used to their advantage. They need not be scientists or engineers, but they do need some basic level of understanding in these areas, and in green chemistry and green engineering in particular, if they are to manage their implementation.

3.1.6 Engineering capacity

In Chinese industry, there has historically been a shortage of research and development personnel. This was one of the reasons that Chinese universities were often actively involved in R&D activities within firms. The increase in the number of trained scientists and engineers in the workforce is lowering this barrier. But despite the large number of engineers who graduate every year from Chinese universities, only 10% are considered to be properly prepared to qualify for positions at multi-national firms (Farrell and Grant, 2005), and some academics interviewed also emphasized the view that internal R&D is limited in many firms (Professor, Beijing University of Technology, 2007, 2008; Professor, Tianjin University, 2007; Professor, Tsinghua University, 2007). Improvements in the Chinese educational system, along with continual increases in the number of students and the enduring popularity of science and engineering as areas of study makes this barrier, in the long-run, one of the least difficult to overcome. Many of the Chinese green chemistry and engineering research groups that collaborate with industry send graduate students to work in the pilot and even full-scale facilities as they move their innovations from laboratory and into the plant. This phenomenon was reported at Tsighua University, the Chinese Academy of Science's Intitute of Chemistry, and Tianjin University, all of whose programs are well-regarded within China. Other groups, such as the one visited at the Southern China University, have students working through the pilot-scale on campus, but contract out with industry for larger scale investigation. In the short term, this is a strategy that can help at least a few firms overcome this barrier, and in the long term, is a way of improving the qualifications of the green chemists and engineers in these programs.

3.1.7 Economic and financial barriers

Development and implementation of green chemistry and green engineering innovations requires investment. Recent work by Yuxiang and Chen has shown that at the provincial level in China there is a link between the overall availability of external financing and environmental performance (Yuxiang and Chen, 2010). While availability of external finance in China has improved since the early 1990's, challenges still remain. Similar to firms (and universities, and governments) throughout the world, those in China have to confront the difficulties of calculating the economic benefits of green chemistry and green engineering. Many of the domestic firms are engaged in lower-value manufacturing, including commodity chemicals, which do not usually have large profit margins. This increases the difficulty in securing the funds to invest in capital improvements to existing facilities. Innovations that require a large up-front investment, or have long pay-back periods, are problematic for many firms. In some of the very competitive areas of manufacturing and production, the investment of time and human resources, in addition to financing, may be beyond their capacity.

3.2 Analysis of the barriers

One challenge with understanding the barriers to these particular technologies is that it can be difficult to disaggregate the barriers particular to green chemistry and green engineering, and those that would complicate innovative activities more generally. There is limited literature on the barriers to these particular kinds of innovations in the Chinese context. The closest is a 1999 study by Ji Wang, which identified five barriers to Cleaner Production strategies (which focus specifically on the reduction of wastes): lack of awareness, regulatory impediments, financial barriers, technological hurdles, and organizational barriers (Ji, 1999). These are consistent, though not identical to those identified above. To better understand factors that are particular challenges for green chemistry and green engineering, the next step is to look to the large body of rigorous scholarship on innovation more broadly. Looking to this literature, it is possible to disaggregate those factors common to innovations in general, and those that are green chemistry and green engineering specific.

From the innovation literature (March and Simon, 1958; Dahlman et al., 1987; Anderson and Tushman, 1990; Gavetti and Levinthal, 2000; Ruttan, 2001; Gatignon et al., 2002; Lall and Pietrobelli, 2002; Poliakoff et al., 2002; Archibugi and Pietrobelli, 2003; Tushman and Smith, 2004), there are several main areas where barriers to innovation are typically located. They are

1. *Organizational barriers*: These involve the ability of those in the firm to search and access appropriate innovations, and also to have a structure (including managerial and technical capabilities) that supports both experimentation and search;
2. *Economic and financial barriers*: These are the barriers that arise from the capital constraints of the firm. There are a variety of costs associated with innovations, beyond the cost of development itself, and they may exceed the expected payoff;
3. *Cultural barriers*: There are nations, industries, and firms that are resistant to new technologies, or lack a culture that provides incentives for innovative activities;
4. *Regulatory barriers*: These occur when regulatory requirements lock firms into particular technology approaches, or when tax or other structures are not favorable to investments in innovation;
5. *Market barriers*: In markets with many competitors, it may be difficult for innovators to recoup the cost of their investment, especially if there is a low value-add to their products. Network effects, monopolies, and other market failures can also create barriers;
6. *Path-dependence barriers*: Innovators are often constrained by earlier investments made by firms and industry into particular technological platforms and processes. The need to interface with existing infrastructures can present a barrier to the development and deployment of new technologies. This can be a particularly important barrier to innovation in some parts of the chemical industry.

Table 2 lists these general barriers along with the green chemistry and green engineering barriers found in China. Many of the barriers described have multiple elements, which come from multiple parts of the "basis set" of general barriers. The "x's" in the table show which of the specific green chemistry and green engineering barriers found in China have elements that correspond with general barriers in the literature.

Table 2- Elements of Barriers to Green chemistry and green engineering in China

		General Barriers to Innovation					
Barrier to Green chemistry and Green Engineering- China		Organizational	Economic/Financial	Cultural	Regulatory	Market	Path –Dependence
	Economic/Financial		x		x	x	
	Competing Agendas	x		x	x		
	Training	x		x			
	Technical Barriers					x	x
	Bureaucratic Incentives		x		x		
	Funding				x		

	Engineering Capacity	x		x			x

Analysis of Table 2 highlights a few important points. The first is that the underlying barriers to green chemistry and green engineering in China heavily overlap with many of the general barriers to innovation. Barriers that are specific to green chemistry and green engineering arise from competing agendas and lack of bureaucratic incentives. These create additional hurdles due to the conflict between policies that demand consistently high levels of economic growth, and the historically weaker priority placed on environmental protection. From a policy perspective, this indicates that policies to support innovation generally will have a positive impact on green chemistry and green engineering. For China, this provides another argument in favor of its current efforts to build up its base of human capital across the board. Capability improvements on both the management and the technical side will be helpful in moving green chemistry and green engineering forward, as will changes in regulations that incentivize innovative activities by firms which locate their activities in China. Additionally, strengthening the stringency, consistency, and enforcement of environmental regulations will also have a significant positive impact on green chemistry and green engineering innovation. These actions would provide greater incentives for development of these technologies on the part of industry. It would also increase the importance of environmental performance for local regulators and bureaucrats. This would help resolve the barriers that arise from competing economic and environmental agendas, and the accompanying problems with the lack of concrete bureaucratic incentives to actively promote the use of green chemistry and green engineering in industrial applications.

In China, where growth and development of the chemical industry are proceeding rapidly, path-dependence and technological lock-in were not cited as the foremost impediments to green chemistry and green engineering. This is contrary to the situation in the United States (Kira JM Matus, 2009). This indicates that the chemical industry in general is more dynamic, with more opportunities for innovation, in China than in other nations, especially the United States and the EU, which already have a large, existing capital infrastructure. This makes the ability to deploy radical innovations in a widespread manner across industry promising in China. A similar situation is occurring in the energy sector, as China works to meet its official goal of producing 15% of its energy from renewable sources by 2015[n]. In an environment where so many factors are undergoing rapid change, a paradigm shift like green chemistry and green engineering runs up against less embedded resistance. The challenge in China is one of awareness, resources and capabilities.

4.1 Conclusions

In China, the major barriers to the implementation of green chemistry and green engineering appear to be those that arise from competing priorities between economic growth and environmental protection as well as the technical challenges from possessing a smaller base of experienced human capital. This is consistent, though not identical to, earlier work to identify barriers to Cleaner Production in China (Ji, 1999). While a relative lack of existing physical

[n] According to the press release "China's Energy Conditions and Policies (December, 2007)", the Chinese government has set a goal of producing 10% of its energy from renewable sources by 2010, and increasing this to 15% by 2015. China "gives top priority to the development of energy technologies, and, in line with the principle of making independent innovations and leapfrogging development in key fields, shoring up the economy and keeping in step with leading trends, stresses accelerating progress of energy technologies and strives to provide technological support for the sustainable energy development." (http://en.ndrc.gov.cn/policyrelease/P020071227502260511798.pdf)

capital presents an important opportunity for green chemistry and green engineering implementation, the flipside of the history that led to this opportunity is that it is still needs to advance the education, training and experience of its scientists and engineers. In the United States and Europe, the level of tacit knowledge in firms is quite high and runs deep; this is the most difficult information to transmit across regions, since it is often uncodified and embedded in the experience of individual scientists, engineers and managers of a given organization.

The problem of sufficient human capital and expertise is one that presents a barrier to innovation more broadly, not just in green chemistry and green engineering. For this reason, any policies designed to positively impact education and training activities more broadly would also be expected to have a positive impact on innovation in green chemistry and green engineering. Policies to strengthen environmental protection and to resolve tensions with economic expansion could also be important drivers for green chemistry and green engineering.

Currently for China, issues of technological lock-in in the chemical enterprise are not perceived as a major barrier to green chemistry and green engineering. In this period of growth, there is an opportunity for alternative designs to compete with the status quo. This does not mean that policy makers, scientists and investors should ignore the issue. In fact, the opposite is the case. The investments being made today, especially in large, capital-intensive facilities, will determine the trajectory of the Chinese chemical enterprise for many decades to come. Choosing to integrate green chemistry and green engineering now, during a phase of rapid growth, is less challenging, and may often be less costly than attempting to incorporate it into established infrastructures later on. However, the fast pace of growth can create a situation that favors proven, existing technologies over greener alternatives that may require time to develop. This dynamic is present, for example, in the energy sector, where despite large investment in greener energy technologies like wind and solar, by far the largest share of new generation capacity comes from coal-fired plants (Zhang et al., 2010, 2011).

Policies that create incentives for the development and/or adaptation of green chemistry and green engineering technologies today would have a long-term impact economically and environmentally. In ten to twenty years, the Chinese may find barriers similar to the ones present in places like the United States, where there are many fewer large, new plants being built, and where it is difficult to make large investments in an existing, aging, and often inefficient capital infrastructure (Kira JM Matus, 2009).

Another aspect of the challenges facing China is the difficulty of conducting transformative research in the current research and development system. The Chinese academic system requires a constant stream of patents and published journal articles by its professors. This discourages them from taking risks on areas of research that have a large potential to be radical breakthroughs, but whose outcome is risky and uncertain. This is exacerbated by the fact that much of the government funded academic research has a mandatory requirement of commercial application demonstration as the main output at the end of the project. Chinese researchers are very responsive to short-term application and industrial research needs because of heavy reliance on industry and funding requirements that emphasize the demonstration of applications within a short time frame. This results in a system of continuous incremental improvements which, while important to overcoming existing technical challenges to green chemistry and green engineering implementation, do not address the large scientific questions for which responses will be needed in the future.

One important, final consideration is the piecemeal and indirect nature of many of the major policy drivers of green chemistry. Green chemistry and green engineering are just one set of responses to policy pressures that encourage, for example, energy efficiency or pollution prevention. Newly released draft regulations for the industrial regulation of toxics, when finalized, may also influence decisions to invest in green technologies that help firms to comply. But all of these different policy areas are largely uncoordinated, and so the responses tend to be targeted at one particular problem or another. Green chemistry and green engineering can be helpful in these areas, but so can older approaches to pollution prevention, or increased energy efficiency. However, one of the strengths of green chemistry and green engineering is that they provide a platform for innovations that can address an integrated set of sustainability criteria, instead of just one problem at a time. But without policies that support that integration, the integrative potential to create solutions to multiple challenges at once is likely to be undervalued. So while the many policy drivers discussed above are important, there is also a case to be made for a more integrated, specific green chemistry and green engineering strategy, so that the Chinese government and industry can develop more effective and efficient ways to address the multiple environmental and health challenges that it faces.

Despite these challenges, green chemistry and green engineering are growing rapidly in China. There is a great deal of potential for both the development of the science, as well as their implementation throughout the chemical enterprise. Green chemistry and green engineering are being actively supported by the government at all levels, through funding for basic research, as well as for a variety of industrially focused research centers and joint industry-university projects. More research is still required to understand how green chemistry and green engineering are taking hold within government, but also within industry. Questions remain about how the presence of multi-national corporations who are active in this area elsewhere, and the demands of major supply chain actors may be influencing development, and potentially removing some of the barriers. Global demand for sustainable products and practices, as well as increased demands for quality, are potential drivers whose influence is not yet well understood in this space. Furthermore, other energy and environmental policies, especially in areas of energy efficiency, are also creating a demand for the kinds of solutions that emerge from the science of green chemistry and green engineering. While they are far from being the norm throughout the Chinese chemical enterprise, awareness and interest continue to expand. There are still important barriers, including laxity of enforcement of environmental regulations in many areas and the lack of any reporting requirements for toxic chemical releases. Changes in these areas, along with a continued investment in building up domestic technical and managerial capacity could have a significant impact in moving China towards the kind of leadership position in green chemistry and green engineering that it is seeking in other related fields such as green energy.

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APPENDICES

Appendix A

Baseline Interview Protocol for Semi-Structured Interviews Regarding Involvement with Green Chemistry

1. What is the current status of green chemistry in your organization (university/department/firm)?
   - How well is it supported (financially)?
   - Are there courses for students? If so, are they required? Do students express interest in the topic?

2. What have you done (in terms of green chemistry)?
   - Role in the project
   - Nature of the green technology (process, product, etc)
   - Level of success (Published? Patented? Implemented? Profitable?)
   - Point of innovation (Basic research, R&D, manufacturing, etc…)
   - Which types have been most successful (or problematic)- if multiple experiences

3. Why did you do it?
   - Internal demand
   - External demand
   - Existence of champions

4. Who did it?
   - Champions- internal and external networks
   - Most essential person(s)
   - How did you (and/or)they become aware of green chemistry?

5. Were there any partnerships involved?
   - Industrial groups
   - Government
   - NGO's, Public Sector
   - External and internal networks (formal, informal)

6. Are there government policies (national and/or local) that have encouraged the development of this project?

7. What challenges did you encounter?
   - Differences in motivations/priorities
   - Technical difficulties
   - Knowledge gaps
   - Funding/financial problems
   - Implementation/infrastructure
   - Firm/Sector/Industry specific
   - Other?

8. What were the surprises?

- What do you wish you'd known at the beginning
- Characteristics of success
- Characteristics of failure

9. What changes would improve it (make it easier to research/innovate/implement green chemistry)?

10. What do you see as the future of green chemistry in China?
11. What changes would kill it (make green chemistry more difficult or impossible)?
12. Who else is good at this? Why?
13. What else should I be asking?

Appendix B: Academic Interviews

Table B.1 Academic Interviews, Organizations and Dates

Title	Date	Institution	Location
Professor	December 1, 2007	Beijing Univ. of Technology	Beijing
Professor #1	November 28, 2007	Beijing Univ. of Chemical Technology	Beijing
Professor #2	July 13, 2010	Beijing Univ. of Chemical Technology	Beijing
Professor	November 28, 2007	Chinese Academy of Sciences- Institute of Chemistry	Beijing
Professor	November 14, 2008	Nanjing University of Technology	Nanjing
Doctoral Researcher	November 14, 2009	Nanjing University of Technology	Nanjing
Professor	December 11, 2008	Southern China University of Technology	Guangzhou
Professor	December 11, 2008	Shanghai Jiao Tong University	Shanghai
Professor #1	November 29, 2007	Tianjin University	Tianjin
Professor #2	November 18, 2008	Tianjin University	Tianjin
Professor	November 29, 2007	Tsinghua University	Beijing

Professor #1	December 3, 2007	University of Science & Technology China	Heifei
Professor #2	December 3, 2008	University of Science & Technology China	Heifei
Post Doctoral Researcher	December 3, 2009	University of Science & Technology China	Heifei
Professor	November 13, 2008	Zheijiang University	Hangzhou
Post Doctoral Researcher	November 13, 2009	Zheijiang University	Hangzhou