Toward Sustainable Anticipatory Governance: Analyzing and Assessing Nanotechnology Innovation Processes

by

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ABSTRACT

Cities around the globe struggle with socio-economic disparities, resource inefficiency, environmental contamination, and quality-of-life challenges. Technological innovation, as one prominent approach to problem solving, promises to address these challenges; yet, introducing new technologies, such as nanotechnology, into society and cities has often resulted in negative consequences. Recent research has conceptually linked anticipatory governance and sustainability science: to understand the role of technology in complex problems our societies face; to anticipate negative consequences of technological innovation; and to promote long-term oriented and responsible governance of technologies. This dissertation advances this link conceptually and empirically, focusing on nanotechnology and urban sustainability challenges. The guiding question for this dissertation research is: How can nanotechnology be innovated and governed in responsible ways and with sustainable outcomes? The dissertation: analyzes the nanotechnology innovation process from an actor- and activities-oriented perspective (Chapter 2); assesses this innovation process from a comprehensive perspective on sustainable governance (Chapter 3); constructs a small set of future scenarios to consider future implications of different nanotechnology governance models (Chapter 4); and appraises the amenability of sustainability problems to nanotechnological interventions (Chapter 5). The four studies are based on data collected through literature review, document analysis, participant observation, interviews, workshops, and walking audits, as part of process analysis, scenario construction, and technology assessment. Research was conducted in collaboration with representatives from industry, government agencies, and civic organizations. The empirical parts of the four studies focus on Metropolitan
Phoenix. Findings suggest that: predefined mandates and economic goals dominate the nanotechnology innovation process; normative responsibilities identified by risk governance, sustainability-oriented governance, and anticipatory governance are infrequently considered in the nanotechnology innovation process; different governance models will have major impacts on the role and effects of nanotechnology in cities in the future; and nanotechnologies, currently, do not effectively address the root causes of urban sustainability challenges and require complementary solution approaches. This dissertation contributes to the concepts of anticipatory governance and sustainability science on how to constructively guide nanotechnological innovation in order to harvest its positive potential and safeguard against negative consequences.
DEDICATION

This dissertation is dedicated to my family for all their love and support.
ACKNOWLEDGMENTS

My work, presented as an individual contribution, is a collective effort. Dr. Wiek, my chair, offered me the skills, courage and strength. Dr. Guston, Dr. Seager, and Dr. Minteer have all guided, instructed and flat out allowed me to do this. I am honored to have these four stellar committee members. There are many fellow students to whom I have turned to in the Transition Lab: Michael Bernstein, Matt Cohen, John Harlow, Nigel Forrest, Braden Kay, Lauren Withycombe Keeler, Rob Kutter, Christopher Kuzdas, John Quinn, Angela Xiong. Then there are those with whom I have collaborated with during the past few years, including: Claire Antaya, Sanjay Arora, Will Barr, Chrissy Bausch, Andrew Berardy, Michael Burnham-Fink, Edward Dee, Troy Hottle, Youngjae Kim, Mindy Kimball, Tomasz Kalinowski, Shannon Lidberg, Chad Monfrieda, Jathan Sadowski, Susan Spierre, Evan Taylor, Tai Wallace, Ben Warner, Annie Warren, Benjamin A. Wender, and Max Wilson. Yet, those are just a few names and there are many more that I hope to stay in touch with. Further, my shadow committee members, Drs. Bennett and Wetmore, who were the best two advisors a graduate student should have had on his committee. Many faculty offered support including Dr. Abbott, Dr. Andries, Dr. Hartwell, Dr. Melnick, Dr. Sarewitz, Dean van der Leeuw, and Dr. Westerhoff. Then there was the endless support from Regina Sanborn and Michelle Anforth (from rides home on Fridays to workshop set up and breakdown) and support from Lori Hidinger. Then there are the hundreds, and I mean hundreds, of citizens, politicians, officials, entrepreneurs, attorneys, investors, scientists, engineers and members of the media who have participated anonymously, and thus, will stay un-named, but are appreciated.
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Chapter 1

Introduction

1. Problem Statement

Cities around the globe are struggling with socio-economic disparities, resource inefficiency, environmental contamination, and quality-of-life challenges. Technological innovation, as one prominent approach to problem solving, promises to address these challenges. Yet, introducing new technologies, such as nanotechnology, into society and cities has often resulted in negative consequences, as societal challenges can be complex, dynamic and intertwined with technological and environmental systems. Cities are where the majority of the humans reside and account for the vast majority of nanotechnology innovation (Wiek, Guston, et al., 2013). Cities function as the initiators and recipients of negative consequences stemming from our most pressing societal challenges. The dynamics of the urban environment, the means and modes of innovation, the future creations and implications of technological innovation and the urban sustainability challenges inform this dissertation.

Academic theories and research efforts often attempt to break problems down by discipline to reduce their inherent complexity. Research methods that isolate selected variables can effectively measure social and physical systems in idealized conditions as a proxy for “real-world” outcomes. Those outcomes inform broader theories about how the world works by describing unique and measurable phenomena. Yet, many of the most pressing societal challenges, today, are “wicked problems” (Rittel & Weber, 1973; Seager, Selinger & Wiek 2012) and demand holistic theories and methods, which in turn demand comprehensive responses. Reductionist approaches are incapable of holistically
addressing complex adaptive systems, such as emerging technologies, socio-technical systems, and sustainability problems, in non-idealized and imperfect ‘real-world’ conditions. More recently, however, research has conceptually linked anticipatory governance and sustainability science: to understand the role of technology in complex problems our societies’ face; to anticipate negative consequences of technological innovation; and to promote long-term oriented and responsible governance of technologies.

Anticipatory governance offers a set of theories and practices to enrich traditional technology assessment methods by focusing explicitly on the societal implications of an emerging technology. The following four design elements comprise anticipatory governance:

1. *Foresight* explores alternative plausible futures often by using scenarios to incorporate values into a spectrum of potential socio-technical outcomes (Selin, 2011; Wiek, Gasser, et al., 2009).

2. *Integration* brings together diverse disciplinary scholars by connecting social and natural scientists or quantitative and qualitative social scientist through socio-technical integration activities, cross-disciplinary workshops and research endeavors (Fisher et al., 2006; Guston, 2008).

3. *Engagement* encompasses a diversity of interactions between scientists, artists, engineers, public citizens, and policy-makers via workshops, conferences, and public events, which are intended to make people aware of what others are doing, and to shape knowledge development, technological innovation, and acknowledge values that impact the creation
of, and reactions to, novel nanotechnologies (Karinen & Guston, 2010; Cobb 2011).

4. *Ensemblization* (the bringing together) of these elements is essential, since the individual components alone are incapable of achieving the same impact.

Sustainability science is an emerging field that starts from a problem-focus and works toward solution-oriented outcomes. A number of design elements inform the theories and practice of sustainability science:

1. *Integrity of human society* is the acknowledgement that urgent challenges are facing the complex relationships among and between human-environment systems and academia must respond through the creation of a new space to address these challenges (Kates, et al., 2001; Clark & Dickson, 2003).

2. *Long-term viability* explores historical, current, and future implications of decisions, actions, and dynamics within and between social and environment systems as a means to understand and to start addressing problems that have inter-generational implications (Komiyama & Takeuchi, 2006; Jerneck et al., 2010).

3. *Normativity* is explicit to the research agenda and value-based principles guiding the research objectives (Gibson, 2006; Norton, 2005).

4. *Transdisciplinary* practices and methods are employed to bridge the science–society boundary in order to initiate and nurture collaborations among and between scientists and stakeholders, writ large, including
industry, government agencies, and civic society. The goal of this approach is to co-construct a shared understanding of the problem, and explore solution options and strategies for implementation (Lang, Wiek, et al., 2012).

5. Place-based research is attuned to the causes and impacts that are observable in differentiated locations embodied at local and global levels (Wiek, et al., 2012).

This dissertation aims to construct and test new theories by merging these two research perspectives in different ways. Wiek, Guston, Frow, & Calvert (2012) and Wiek, Guston, et al. (2013) started to link anticipatory governance to sustainability science. Those earlier discussions focused on the elements that are compatible, yet nuanced differences readily appear when these two research perspectives are considered as adjoining building blocks. Here I review, briefly, the compatibilities and differences before obscuring the boundaries between anticipatory governance and sustainability science.

The attention paid by anticipatory governance to societal implications of emerging technologies and the problem-orientation of sustainability science is quite compatible. Yet, anticipatory governance is more narrowly focused on a particular set of challenges embodied in emerging technologies, while sustainability science addresses the integrity of human societies more broadly. Agreement is also observed between the elements of foresight and long-term viability as both look to get out in front of upcoming challenges with the hope of building capacity to take decisions with future implications in mind.
The integration, engagement and transdisciplinary elements all attempt to bridge disciplinary and science–society boundaries. Yet, a first nuanced difference is observed as anticipatory governance elicits and extracts societal values through public engagement to guide collective decision-making. Sustainability science further engages with societal values through engaged-research contrasting and challenging public values against normative principles of sustainability.

There is ambivalence in the compatibility between place-based research for sustainability science and anticipatory governance. Anticipatory governance often investigates emerging technologies in connection to activities in specific places (i.e. laboratories (Fisher et al., 2006) or patent offices); yet, the results of nanotechnology innovation include knowledge and technological artifacts that impact a complex global science and technology enterprise, as well as society more broadly. All the while, sustainability science is grounded by place-based research with impacts observed discretely in localized contexts with links to global environmental systems. The links across scales causes this ambivalence in comparing the issue of place-based research in both sustainability science and anticipatory governance.

The dissertation takes a holistic and systemic approach to ‘wicked problems’ and the knowledge domains of anticipatory governance and sustainability science serve as launching pad for this research endeavor.

However, previous research approaches exhibit certain insufficiencies,

- Studies on technology innovation usually are not from a contemporary, “real-world”, perspective that holistically account for: the innovation processes that are happening; the actors involved, their activities and drivers; the places
where technologies emerge and decisions manifest; and all the critical stages within that process (Chapter 2).

- Three bodies of literature (risk governance, anticipatory governance, and sustainability-oriented governance), among others, are attempting to ‘guide’ emerging technologies. This knowledge is scattered over different strands of literature and, without appropriate operationalization, these guidelines remain largely intangible and unused by entrepreneurs, researchers, and regulators engaged in nanotechnology innovation processes. (Chapter 3).

- Intuitive scenarios based on logical and creative thinking aim to explore futures through compelling stories, however, they often lack the coherent and systemic focus of analytical scenarios. Conversely, analytical scenarios often fail to resonate with stakeholders, leaving the message unheard. (Chapter 4).

- The claims made by those promoting nanotechnology investments in science, technology and innovation neglect to sufficiently acknowledge that sustainability problems are neither simple nor merely complicated, but are rather truly complex in structure (Chapter 5).

These identified gaps in the literature and the challenges facing our cities demand a response and inform the scope of the dissertation.

2. Research Objective and Research Questions

This dissertation aims to advance the conceptually and empirically links between anticipatory governance and sustainability science by focusing on nanotechnology innovation and urban sustainability challenges. This objective is supported by the broad
research question: *How can nanotechnology be innovated and governed in responsible ways and with sustainable outcomes?*

To break this broad research question down, I ask for sub-questions that guide the dissertation:

1. How is nanotechnology currently innovated and governed in the urban environment? (Chapter 2)
2. How well does the current governance and innovation regime perform against principles of risk, sustainable, and anticipatory governance? (Chapter 3)
3. What could be future implications of a continuation of the current innovation and governance regimes and how might they contrast with alternative models? (Chapter 4)
4. What are necessary changes to innovate and govern nanotechnology in responsible ways? (Chapter 5)

3. Research Design and Methods

The research design is comprised of four independent, yet interlinked, studies that comprise the totality of the dissertation. The research takes a sustainability science perspective (Lang, Wiek et al. 2012) by starting with a problem-based approach and moves to appraise solution-oriented interventions. Each chapter draws from and builds upon the following research perspectives; sustainability science, technology assessment (specifically, anticipatory governance) and innovation studies (using process analysis). The chapters analyze, assess, co-construct scenarios of governance, and appraise the supply of nanotechnology for urban sustainability demands (see figure 1.1).
Figure 1.1. Conceptual framework and components of the dissertation.

Sustainability science is a recently conceptualized knowledge domain (Clark & Dickson, 2003) born, largely, from adaptive management (Norton, 2005) and broad socio-ecological values (Gibson, 2006; WCED, 1987). Sustainability science is explicitly normative in its orientation and moves from analyzing complex, systemic problems to actively engaging in and testing plausible solutions (Lang, Wiek, et al., 2012). This dissertation advances the theories and practice of sustainability science research with an explicit focus on emerging technologies.

Technology assessment is informed by myriad theoretical concepts. This dissertation draws on the theoretical and practical construct of real-time technology assessment (Guston & Sarewitz, 2002). Real-time technology assessment has been brought into practice through anticipatory governance (Guston, 2008; Fisher et al., 2008)
and is central to the work presented here. Anticipatory governance is a vision for the creation and use of a set of capacities that build *foresight* through knowledge *integration* between natural and social sciences and formally designed and supported *engagement* among citizens, artists, engineers, scientists, policy-makers and corporations, to name a few. This dissertation explores the normative dimensions of sustainability science through many of the practices of anticipatory governance.

The four substantive chapters that comprise the dissertation rely upon a diverse set of methods to address the research question. Literature reviews were conducted prior and during all research efforts. Participatory research methods were employed to study the innovation system, to assess the governance regime and in the construction of scenarios. Interviews, workshops, focus groups, and walking audits with subject area experts were leveraged in every study. Quantitative and qualitative methodologies are leveraged to address the research questions.

Research was conducted in collaboration with representatives from industry, government agencies, and civic organizations. Each and every study depends on participatory research methods, as defined in Talwar et al. (2011), in different ways and to various degrees. Chapter 2 brings stakeholders to the fore in the interviews and offered participants an opportunity for reflection upon initial findings in a consensus workshop setting. Chapter 3 brought together interdisciplinary scholars from the life science, engineering, physical sciences, science, social science, design school, and sustainability science in a workshop setting to assess the governance of nanotechnology innovation. Chapter 4 crafts future scenarios with inter- and trans-disciplinary participants through interviews (one-one), workshops, public events and public
engagement exercises. Chapter 5 offered opportunities for participation in interdisciplinary workshops to scholars from social and physical sciences and to transdisciplinary stakeholders from the fields of healthcare, environmental remediation and renewable energy in three walking audits.

4. Individual Studies

4.1. Nanotechnology Innovation: Governance by Stakeholders within a Metropolitan Area. Real-time technology assessment, a central design element for anticipatory governance (Guston, 2008) and sustainable governance (Wiek et al., 2007) primarily guide Chapter 2. The chapter’s objective is to analyze the nanotechnology innovation process from an actor- and activity-oriented perspective by asking the following question: Who (actors) is currently doing what (activities) and why (enabling and constraining factors) in the process of nanotechnology innovation (applications) in metropolitan Phoenix? Interviews with subject area experts and literature reviews provide the data for this study.

4.2. Responsibilities in Innovating Nanotechnology. Three bodies of literature (risk governance, sustainability principles and anticipatory governance) inform a comprehensive design framework that is employed in Chapter 3. The goal of this chapter is to assess the current nanotechnology innovation and governance regime using the triple bottom line of sustainability and the synthesized set of normative responsibilities. The research question asks: Can these diverse literatures be synthesized and employed as an appraisal tool to assess the governance of technological innovation? Literature reviews, interview data, and provide the data for the literature synthesis, agent network analysis and value mapping exercise in the study.
4.3. Nanotechnology and the City: Governance Scenarios. The conceptualization and exploration of future scenarios is the focus of Chapter 4 and offers a means to enhance foresight for urban innovation practices (Wiek et al., 2009; Sandler, 2009; Selin, 2011). The goal is to construct a small set of future scenarios to consider future implications of different nanotechnology governance models. A research question can be asked: What could be future implications if the current dominant innovation and governance models continue, or, in contrast, if alternative ones would emerge? And how conducive to responsible innovation and anticipatory governance are these different models? Participatory scenario construction methods informed this study’s findings.

4.4. Nanotechnology for Sustainability: What Does Nanotechnology Offer to Address Complex Sustainability Problems? In Chapter 5, the conceptualization of sustainability problems as wicked problems that demand responses from science, technology and innovation practices is constructed based upon the supply – demand model of science policy (Sarewitz & Nelson, 2008). The objective is to appraise the amenability of sustainability problems to nanotechnological interventions. A research question is asked: How will nanotechnology applications intervene into complex urban sustainability problems and what outcomes can be anticipated? Workshops, interviews, literature reviews and walking audits provide the requisite data for this study.

5. Value Proposition

By tackling this set of questions, the dissertation addresses the identified shortcomings in the conceptualizations and practices of innovation studies, disconnects between disciplines working toward responsible innovation, a lack of scenarios that focus on governance, and an analytical tool to appraise technological interventions. The
philosophical and empirical work encapsulated within the dissertation builds upon sustainability science and anticipatory governance and draws upon risk governance. The individual chapters each contribute novel theoretical concepts to scholars and offer tools to practitioners. Chapter 2 offers a means to structure and evaluate qualitative narratives on innovation processes and practices, while reflecting the collective mental model held by practitioners innovating nanotechnology. Chapter 3 bridges the knowledge domains of risk governance, sustainability science and anticipatory governance to create a comprehensive set of normative responsibilities for emerging technology governance and then assesses the current governance regime in a novel way. Chapter 4 shows that path dependency will perpetuate the current sustainability challenges, while alternative forms of governance may have positive and lasting implications, if stakeholders come together in an effort to collaboratively solve problems in the city. Chapter 5 shows that nanotechnology innovation is not enough to address urban sustainability challenges. The dissertation offers the requisite knowledge to analyze, assess, construct scenarios, and appraise nanotechnology innovation in an urban context. This dissertation contributes to the concepts of anticipatory governance and sustainability science on how to constructively guide nanotechnological innovation in order to harvest its positive potential and safeguard against negative consequences.
Chapter 2
Nanotechnology Innovation: Governance by Stakeholders within a Metropolitan Area

1. Introduction

Cities across the United States currently face a diverse set of challenges from economic stagnation to aging populations and from increasing energy demands to environmental degradation. Technology is commonly used to address some or all of these challenges, including new and emerging technologies, such as nanotechnology (Wiek, Foley, et al., 2012). City officials, university researchers, health care providers, economic development agencies, private investors and others shape how technologies emerge in the city through decisions taken in the course of their daily activities. Government agencies can regulate laboratory practices in cities, university partnerships with local healthcare facilities offer an opportunity to explore novel technologies, and investors can lure entrepreneurs into moving in or away from a city.

Traditionally, innovation studies focus on specific technological sectors and innovation processes from a macro perspective. Abernathy & Townsend (1975) followed innovations in railroad and computer technology with historical analysis. To better understand current activities, scholars have more recently shifted to contemporary studies that address the governance of emerging technologies. Scholars most often analyze national and international level decision-makers (Nelson, 1993). Those levels are often disconnected from places where practical decisions are taken on a daily basis in regional innovation systems (Cooke & Morgan, 2011). Innovation studies connected to practice often focus on single regulations – e.g. Jaffe (2000) explores the influence of the Bayh-
Dole Act. Others have focused on isolated actors – e.g. Fisher’s (2007) work with laboratory scientists. Still others focus on transition points between phases – technology transfer from universities to the private sector (Feldman & Massard, 2002).

However, this body of literature has not taken a holistic approach to couple these “real-world” perspectives including: addressing real-time innovation processes, focusing on the actual decision processes, connecting to the places where they happen and play out. New concepts such as real-time technology assessment (Guston & Sarewitz, 2002), practice-oriented analytical approaches (Robinson, 2009), place-based technology development (Wiek, Guston, et al., 2013), and whole product design (Graedel & Allenby, 2010) provide guidance for how to overcome the outlined deficits. A real-time perspective to technology assessment helps to overcome delays between technological innovation and governance efforts (Grieger, et al., 2010). The practice-oriented analytical perspective is based on the obvious fact that innovation happens through people, their decisions and actions within their spheres of influence (Robinson, 2009). From here, we argue that if innovation ought to happen somewhat differently (with somewhat different decisions and actions), namely in more anticipatory and responsible ways, we first need to know who is doing what (and why) within the innovation process. The place-based perspective centers on places as ‘hubs’ where people interact and are ‘invested’ in life and work; where similar socio-cultural and socio-political forces reign; and where emerging technology arise and transform society. The holistic approach shifts attention away from specialization and segmentation of innovation to a model that accounts for all stages of innovation (c.f. chain-link model Kline & Rosenberg (1986)) and thereby
allows for more systemic analyses to avoid blind spots by understanding the previous and ensuing consequences of technological innovation.

This study addresses the following research question: Who (actors) is currently doing what (activities) and why (enabling and constraining factors) in the process of nanotechnology (applications) innovation in metropolitan Phoenix? This is an intermediate question, which creates the basis to explore how to co-construct governance arrangements and enable responsible innovation (Wiek, Guston, et al., 2013). The study applies a simplified framework from institutional analysis (Ostrom, 2009; Wiek & Larson, 2012). The who-question identifies key actors, defined as stakeholders with critical roles in the innovation system, and their positions within the nanotechnology innovation process. The what-question draws out the activities (decisions, actions, or reactions) performed by the actors. The why-question teases out constraining and enabling forces that drive actors to take the actions they take. And all of these questions are addressed from a real-time, place-based, and holistic perspective as outlined above – with the ultimate goal to explore how constraining and enabling forces and actor collaboration could be changed and complemented in ways that would enhance innovation activities in anticipatory and responsible ways. We conducted and analyzed data from 45 interviews and an interactive review workshop with a sub-sample of the interviewees.

Cities have been the nexus of creativity, technical and non-technical innovation, as well as wealth generation for millennia (Kotkin, 2005). Hundreds of cities are fostering cultures of innovation, drawing talent, economic opportunity, and recognition to their place in the world as regional innovation centers (Porter, 1990). Yet, a counter
argument to our place-based study could be that emerging technologies are not emerging in *one* place and are, in fact, being shaped by national, international, and even global processes and networks (Markard & Truffer, 2008; Dunning & Lundan, 2009). Our approach is not blind to the broader forces operating at higher levels (from a multi-level perspective) than cities, and therefore allows for activities occurring outside this boundary to be captured. Despite a leaky boundary between cities and the broader world, cities continue to be proven leaders and catalysts for regional innovation clustering and economic success (Link, 2002; Felbringer & Rohey, 2001; Avnimelech & Feldman, 2010). Florida (2008) points out that a city’s “creative economy” is a critical success factor for career options. This reinforces the point that social networks (while maintained in virtual spaces) are forged in real places of learning, recreating, and working – all of which happens in the city.

Nanotechnology, the selected unit of analysis for this study, is an agglomeration of nanoscale science and engineering activities funded by the U.S. National Nanotechnology Initiative (Clinton, 2000). This has resulted in the U.S. Patent and Trademark Office (USPTO) creating a new classification for patents that leverage nanotechnology (Bawa et al., 2005). Additionally, the search terms that defined by Porter et al (2008) can describe a significant increase in peer-reviewed publications that draw together a diversity of disciplines that intersect with nanotechnology as a common denominator. Further, Youtie & Shapira (2011) demonstrate the connection of nanotechnology patenting and publishing with urban innovation clusters.

Metropolitan Phoenix was selected as a case study for several reasons, substantive and pragmatic ones. The first was pragmatic as metropolitan Phoenix offered a unique
opportunity for frequent engagement between local actors and researchers to enhance the collaboration, networking, and collective reflection process. Second, city leaders in metropolitan Phoenix are seeking to revitalize the economy by clustering high-technology companies as suggested by Felbringer & Rohey (2001). Third, Phoenix is one of the top thirty nanodistricts in the U.S. (Youtie & Shapira, 2011). Fourth, metropolitan Phoenix is home to city, county, and state levels of government involved in technology funding and regulatory activities. Fifth, Arizona State University launched an effort to create a “New American University” with a strong commitment to generate use-inspired knowledge to help solving problems in metropolitan Phoenix (Crow, 2010). Finally, there are several university partnerships that allow for in-depth analyses of nanotechnology innovation in metropolitan Phoenix, involving, for example those universities, healthcare facilities and private research laboratories fostering personalized genetic medicine. Additional partnerships are dedicated to the research, development and production of nano-enhanced solar energy. There are also collaborative activities that directly explore governance issues of nanotechnology. While these characteristics make metropolitan Phoenix a viable case study to explore nanotechnology innovation, it also allows for drawing general conclusions and transferring insights from this case study to other urban innovation districts.

The study’s broader purpose is to demonstrate how to create baseline data in support of anticipatory governance and responsible innovation of emerging technologies in general, and nanotechnology in particular. By engaging a diverse set of actors the study also provides opportunities for shared understanding of the current structures and
shortcomings in technology governance in metropolitan Phoenix. Finally, the study critically reflects on the added value of a place-based approach to technology innovation.

2. Case Profile: Technology Innovation in Metropolitan Phoenix

Phoenix’s history is rooted in the technological feat of canal building completed by the Hohokam peoples between 450AD and 1400AD, and the city’s name reflects the rise of a new society out of the ashes of the Hohokam (Redman, 1999). The creation of the Roosevelt and Hoover dams, built in the early 20th century, provide water and energy. Two other factors contributed to Phoenix’s population explosion – air conditioning and inexpensive housing (Gober, 2006). In 2010, Maricopa County was the home to just over 3.8 million people and the fourth most populated county in the United States (US Census, 2010). Today, the five C’s (climate, copper, cattle, citrus, and cotton) that defined the first century of Arizona’s economic development are up for debate (Beard, 2012). The study engaged key actors and organizations seeking to reshape the next century of economic development with an emphasis on technology-based industries, including nanotechnology.

Technology-oriented companies took root in the mid-1960s, as the Motorola Corporation relocated to Phoenix. Honeywell, Boeing and other aerospace and electronics firms soon joined Motorola as part of a national plan to relocate military and defense manufacturing sites away from the coasts (Luckingham, 1989). In the late 1980s, Arizona State University in Tempe was the home to a flurry of nanotechnology innovations in microscopy (Lindsay, 2010). A robust knowledge set and skilled labor force dedicated to semi-conductors flourished. Intel established facilities in Chandler, reinforcing the regions semi-conductor industry, in the 1980s. However, from 1950 to
2005, housing and land development remained the primary economic forces in metropolitan Phoenix (Gober, 2006). Technology-based enterprises, while certainly valued and recruited from outside Phoenix, were not incubated within the metropolitan region. A positive unintended consequence is that a strong social network of ex-Motorola employees has become today’s leading entrepreneurs, patent attorneys, and investors – akin to Avnimelech & Feldman (2010) findings. A negative unintended consequence is the large plume of chlorinated hydrocarbons forming the Motorola 52nd Street Superfund Site in downtown Phoenix, a legacy of historically poor waste disposal decisions (EPA, 2011).

Metropolitan Phoenix houses city, county, and state government agencies, most of which have policies in place to recruit and retain high-technology companies, including companies working with manufactured nanotechnology products. A variety of companies and networking organizations acknowledge working with nanoscale materials as defined by Lindsay (2010). In addition to Intel, Honeywell, and Boeing, locally based nanotechnology companies include large firms (e.g., On-Semiconductor, Microchip, Rogers Corp., Abraxis BioSciences) and numerous small to midsize firms. The Arizona Nanotechnology Cluster is a networking group that meets monthly in Tempe and Tucson with 20-30 members attending the public lectures on nanotechnology. The Arizona Biotechnology Association runs frequent activities with 25-50 members and conducts larger semi-annual events with hundreds of members attending. The Arizona Technology Council lobbies for technology-oriented companies, publishes a quarterly magazine, and has over four hundred members. They administrated the first Arizona Science Festival in 2012, as part of Arizona’s centennial celebration. These organizations are the underlying
social network of a community dedicated to technological innovation as a means to support the local economy through entrepreneurial and corporate growth. Metropolitan Phoenix is one of the top thirty nanodistricts in the U.S., based on patent and publication data analysis (Youtie & Shapria, 2011). Patents issued by the USPTO between 1975 and 2010 (and assigned a nanotechnology classification) were catalogued by Lobo & Strumsky (2011). All patents with an Arizonian inventor were extracted from that dataset, resulting in 152 patents. A census of these patents reveals:

- 17 patents issued to sole authors living in metropolitan Phoenix
- 45 patents issued to co-authors living in metropolitan Phoenix
- 1 patent co-authored between inventors living in two different counties in Arizona, i.e., metropolitan Phoenix and metropolitan Tucson
- 27 patents issued to co-authors, with one party living in metropolitan Phoenix and one living outside of Arizona
- 62 patents issued to an Arizonan inventor not living in metropolitan Phoenix

This reinforces the boundary of metropolitan Phoenix as an innovation district with strong internal (45 co-authored patents) and external (27 co-authored patents) collaborations. Phoenix’s output of patents is in the second tier of US cities (behind San Francisco, Boston, New York, Philadelphia, and Chicago), similar to San Diego, CA, Austin TX, and others (Youtie & Shapira, 2011). There is a diversity of organizations (e.g. academic, entrepreneurial and corporate initiatives) working across a number of sectors (e.g. in semi-conductors, defense and aerospace applications, and nano-enabled medicines). The presence (or absence) of actors and sectors is largely unknown and is a point for analysis. Four
hundred organizations working directly and in support of nanotechnology innovation make Phoenix a center of activity in nanotechnology were cataloged for this study.

3. Research Design and Methods

Guston & Sarewitz, (2002) first introduced real-time technology assessment and offered the broad research question – who is doing what – as a means to address innovation activities as they are happening. We ask this question within a framework that adopts the chain-link model of innovation (Kline & Rosenberg, 1986) with the additional governance conditions (constraining and enabling) offered by the chain-link+ model (Robinson, 2009). This model structures nanotechnology innovation as a sequence of phases, linked by process-outcomes, which are bounded by constraining and enabling factors. Based on institutional theory, the framework captures six analytical elements, namely, nanotechnology application, phases in which actors perform activities that are shaped by barriers and carriers. Fig. 1 shows the framework presented to interviewees, the superimposed questions were asked verbally to capture the analytical elements. The impact of the innovation structure used with participant’s responses is reported in the results and briefly discussed in closing.
Figure 2.1. Framework for eliciting and analyzing data on nanotechnology innovation. Figure adapted from Robinson (2009) chain-link+ model.

The study draws its participant-based methods of semi-structured interviews and a synthesis workshop from work developed by Wiek, et al. (2007). Research was conducted as a case study on metropolitan Phoenix, but incorporated processes outside this geographic boundary, including actors in distant regions (e.g., suppliers), higher authorities (e.g., federal agencies), and global network processes (e.g., for distribution). Innovation activities were mapped by location (within or outside metropolitan Phoenix) to assess the place-based orientation of nanotechnology innovation activities in a bimodal manner.

Interviewees were selected from ca. 400 identified organizations engaged with nanotechnology innovation in metropolitan Phoenix. These organizations were assigned to nine predefined actor groups: industry, academia, legal and business consultancies,
insurance companies, government regulatory agencies, government funding agencies, civic organizations, media, investment companies. A sample of 143 organizations from the larger population was randomly selected and solicited for interviews. A total of 45 individuals from the nine different sectors responded to the solicitation and in-person interviews were conducted at mutually agreed upon locations near their place of employment. All interviewees lived and worked in metropolitan Phoenix at the time of the interviews; yet, many represented organizations transcending the defined boundary as they belong either to higher government levels (state or federal), or to private enterprises with higher levels of organization (national and international).

The interviews started by reviewing the interviewee’s background information and focused then on the guiding questions of the innovation process framework (Fig. 1). The interviewee was asked to identify who did what from the ‘start’ of the innovation process to the ‘end’. Participants were encouraged to rebut the presumptions that innovation had a start or an end or distinct phases. Participants described, in their own words, the innovation process in general, and then illustrated the process with a specific case of their choice.

Two months later, all interviewees were invited to a synthesis workshop held at Arizona State University campus to review the interview results, drew conclusions, and explored future collaborative activities. The workshop had representation from industry, academia, legal and business consultancies, government regulatory agencies, government funding agencies, and investment companies with 10/45 interviewees participating in the consensus workshop. The workshop consisted of a brief introduction, reporting initial results, and discussion in a semi-structured format.
Two forms of data were analyzed, the worksheets with the interviewer’s notes and the transcripts of the interview (37/45 gave permission for audio recording). Worksheets were identified as TH: theoretical or CS: case-specific. Case specific worksheets were grouped by sector (i.e. automotive, medicinal, semi-conductor). Every analytical component was identified and catalogued by worksheet. An activity-based phase, identified in all but two interviews, offered a point of alignment across all interviews. Analytical components were clustered by one researcher and validated by a second researcher for inter-rater reliability. Audio recording were summarized and selected interviews were transcribed for supporting quotations.

4. Results

The rationale for city leaders to support high-technology innovation is simple – it provides an alternative to the roller coaster land development scheme experienced in Phoenix throughout the past thirty years. Emerging technologies also promise to solve problems that the city faces. But metropolitan Phoenix offers more reasons to engage in high-technology innovation. Arizona has vast solar resources, latent investments in solid-state physics and semi-conductor manufacturing, and an affluent retiree community dependent on healthcare services. These are all opportunities around which a culture of innovation is being centered. The rationale for actors to engage in nanotechnology innovation within a metropolitan area is simple but the process of innovation is not.

Results show that actors follow preconceived mental models of innovation and governance (e.g. technology-push, market-oriented, technology-transfer, and closed-collaboration). The findings do not propose a linear innovation model. Rather, the findings report on a complex set of phases that are iterative, dynamic, and overlapping,
but nonetheless sequential. Narratives described the iterative activities in terms of restarts, trials and errors, and the repetition of activities within and between the phases. Stakeholders expressed dynamism in the ever-changing conditions, such as the arrival of a new business partner or technological advances that allowed (or prevented) innovation from continuing. Interviewees explained overlaps as moments when the intended outcomes from one phase were accomplished and a boundary was crossed. At that point a new set of actors with a new set of activities were needed. The narratives consistently articulated an originating point and an intended goal and a set of sequential phases that occurred overtime despite the iterative, dynamic, and overlapping characteristics.

Stakeholders are situated in a distinct and meaningful sequence that is socially constructed to influence the progression of nanotechnology innovation in particular ways. The study’s analytical components reveal the differences between the linear innovation model and the rich and complex sequence described in the narratives.

4.1. Nano vignettes. For an initial overview and orientation, we provide a set of direct quotations from the interview transcripts. These ‘vignettes’ illustrate the complex interplays of phases, actors, activities, carriers, and barriers; the breadth of actors directly and indirectly involved in nanotechnology innovation; the multiple actor perspectives; the wide variability in nanotechnology applications (even within one sector). The following statements all refer to nanotechnology applications in the solar energy sector.

“I think [nanotechnology innovation] starts with problems and it links to ideas and potential solutions. I don’t think there is any limitation [to who can identify the problem]. And I think that academia has more latitude to think about problems
they want to think about, whereas there is a constraint of innovation [in industry] as industry is market-driven, usually.” (Government funding agencies; no. 5)

“Sometimes [academic researchers] don’t have that kind of time for this idea bouncing […] we don’t have that culture. We really don’t. And then maybe we are missing something because of that.” (Academia / Research; no. 4)

“Do you see what the problem is – we are totally reliant on fossil based energy. We must find ways to tip the scales and drive the solar economy.” (Government regulatory agencies; no. 2)

“There are definitely barriers to recognizing problems. There are a lot of problems in the world. So which ones you focus on is up to you. Apathy is a big barrier to recognizing problems. A lot of people want to sit there and watch TV and tell me to go away. People just want to live their lives and they are not out to solve the world’s problems.” (Civic organizations; no. 1)

“The big idea for the state, which is not a bad one, is instead of mining copper, let’s mine the sun. It is a great idea, but the funding mechanism for it is stalled.” (Government funding agencies; no. 2)

“We have been working on a platform, let’s say, where we add nanoparticles to liquids and this is for purposes of solar energy conversion. The idea is that by adding these nanoparticles, say to water, you can enable the sunlight to be adsorbed directly into the suspension of nanoparticles and thereby making the process of converting sunlight into heat more efficient. Actually, it was the modeling that suggested this would be a good idea. We have never been able to test this idea on, I would say, a large scale.” (Academia / Research; no. 4)
“We are doing development work on growing algae for food and fuel. It is a small start up company right now. The reason I like start ups is that they are small. I want to spend my time doing something that hasn’t been done before, you know. I get a charge out of that. Typically when you get to that phase [scaling for commercialization] you go from 30-40 people that are all driven, like-minded, everybody has the same brass ring in mind. Everyone has somewhat of alike personality – a little bit like cowboys – because start ups are risky.” 
(Industry; no. 7)

“In our profession, we are the first line of defense in helping companies mitigate the issues, problems, risks before they get to litigation or to legal situations. Customers may ask for proof of insurance in case there is a problem with the product. Think of insurance as a form of security.” (Insurance companies, no. 1)

“The company was considering putting this big [solar] manufacturing facility in [Arizona town] or New Mexico. But, they were really pushing the governments in those states to offer them the best deal to create the jobs they were going to create. They got some significant tax breaks from the State of Arizona to be here.” (Civic organizations; no. 1)

“In workforce we have people doing training on how to get and keep a job that have no idea what the new normal looks like for job seekers. It is all about social networks and how you need to research companies and understand your value proposition. Once you build this solar mining plant […] only five percent of the people need to stay on board after it is all built out. It is a cool idea for bringing
income to the state. It is not a long-term solution to the workforce problem.”

(Government funding agencies; no. 2)

“Today, now we are getting into next generation thin-film testing and this is where it gets to the nano piece. As PV evolves […] into a more sophisticated platform, they are setting up suites in the sort of nano testing area. The ultimate success of [company name] is to move into that space and begin testing.”

(Academia / Leadership & Support; no. 2)

The vignettes illustrate some key features of the innovation process, from the idea to the use of nanotechnology applications and beyond to the maintenance and repair of durable products. The city, metropolitan Phoenix, serves as an organizing mechanism for nanotechnology innovation activities – all actors work and interact with each other within the city. And they work on similar challenges, albeit from different perspectives, namely, to leverage local resources to generate solar energy; to overcome incumbent energy supplies; to generate local employment; and to generate profits. But quickly we understand that these perspectives are often in tension, competition, or conflict with each other. For instance, the freedom of academics to think about ideas is contested between the first two speakers – one from government and one from academia. In addition, there is a variety of solar energy nanotechnologies competing for limited resources and support, including nanoparticles suspended in liquid to convert heat to energy; genetically modified algae grown for liquid fuels as a replacement for gasoline; and thin-film photovoltaic panels for electricity generation. The vignettes also illustrate that while there is a diverse set of individuals and organizations working directly on nanotechnology for solar energy, there is an additional set of actors that are indirectly involved in insurance,
workforce development, company recruitment, regulatory capacities, and issue advocacy. They all are part of and make contributions to the innovation process; yet, their involvement and influence are very different. And finally, some actor groups that might be of importance seem to remain widely unrecognized in the innovation process (e.g., consumers).

4.2. Sectorial differentiation by nanotechnology applications in Phoenix. The vignettes above illustrate nano-enhanced solar energy innovation in metropolitan Phoenix. Another orchestrated network of university researchers, economic development officers, industry executives, healthcare providers, and corporate investors has coalesced around personalized medicine in metropolitan Phoenix. Their efforts have created a technology roadmap to stimulate economic development specifically for this region and secure investments from academia, government and private funders (Flinn Foundation, 2012). This roadmap illustrates how actors are organizing themselves based on the geographical unit of the city (metropolitan Phoenix) to plan, promote, and execute an innovation policy predicated on personalized medicine.

“Personalized medicine […]: Sometimes luck plays a role. [He] wanted to come back to Arizona after running the [program] at NIH. And so just a handful of people [names removed] started building the thematic area.” (Private investment groups; no. 3)

“We should talk about the idea of personalized medicine. In the past a lot of drugs were discovered because people stumbled across molecules that had efficacy against different tumors cells. The tide is turning to where we are able to
analyze a person’s genetic structure and determine different disease states. This is what has changed.” (Industry; no. 6)

“The [Company] stopped the testing. So I called [Company President]. I have known [him] for quite some time. With a half a million deaths, you are talking about a million women at risk of dying. Why did they stop pursuing the drug? Because they ran out of money, […] I didn’t want them to stop a thirty-two patient study.” (Academia / Research; no. 5)

The excerpts illustrate that the actors are focused on a specific sector – personalized medicine, even when discussing collaboration. They do not refer, in any significant way, to other sectors of innovation. This makes actors difficult to pull apart from the specific technological and economic goals of their product-based sub-network. The sub-networks of personalized medicine and renewable energy meet separately to share information and collaborate in sector forums organized by the Greater Phoenix Economic Council (GPEC, 2012). Overall, the nanotechnology innovation network is divided along product-based sectors distinguished by economic development planning. This limits overlap and synergies between sub-networks, creating disconnects in the overarching governance regime.

The actor network centered on personalized medicine and engaged with nanotechnology applications also exemplifies the myopic focus on commercialization as the sole mechanism to bring value to the public. Table 1 illustrates that despite the sector (i.e. solar or personalized medicine), the terminal goal is always commercialization (Phase V). Defense applications are the exception, where the term is operationalization, bringing nanotechnology into military operations. Such a commercialization-oriented
governance regime of nanotechnology innovation fits into the “economics of technoscientific promise” (Felt, et al., 2007). Nanotechnology innovation as currently conceived is attempting to leverage techno-scientific promises into economic benefits. This characteristic defines the orientation for all theoretical and empirical expressions of nanotechnology innovation by the participants. Participants mentioned social benefits as the secondary outcome that resulted from commercialization. No one discussed a non-commercial means to realizing social benefits, such as the efforts by the late Joseph Salk (among others) and the World Health Organization to globally distribute a polio vaccine as a social good (Boettiger & Wright, 2006).
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<th>Sectors</th>
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<td>Evaluate per regulations (5:4)</td>
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<td>Semi-conductor &amp; Electronics (n=10)</td>
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<td>Analyze the problem</td>
<td>Meet scalability challenges</td>
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<td>Automobile Enhancing (n=7)</td>
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Note. In parenthesis is the number of interviewees who contributed to the respective narrative (out of 45 interviewees) by phases, dominant activity, and ratio of activities that occur in Phoenix to not in Phoenix.
The city, a place-based organizing mechanism of nanotechnology innovation, is comprised of six differentiated sectors where more than one interviewee provided an empirical narrative. The six cases are personalized medicine, renewable energy solutions, semi-conductors and electronics, automobile enhancements, aerospace and defense, and water filtration (Tab. 1). The interviewees specified innovation activities occurring in metropolitan Phoenix and not in Phoenix. This place-based analysis shows that in metropolitan Phoenix, the greatest opportunity for influence by the actors within the region is “upstream” – in the first three phases of innovation. The ratio shifts after the third phase to activities outside of Phoenix, signaling that the regional actors have less control over commercialization.

Analyzing the data by product sector demonstrates a strong alignment with four different ‘ideal-type’ innovation models, shown in the right-hand column of Table 2.1. The provided framework (see Fig. 1) offered the flexibility for alternative “mental models” of nanotechnology innovation and governance to emerge (Gorman, 1999). Stakeholders within a given sector consistently named similar constellations of the study’s analytical elements in similar sequences. The inclusion or exclusion of certain actors, such as the exclusive sale of manufactured nano-products to government buyers indicated closed collaboration, and thusly aligned with the aerospace and defense sector. Similarly, the originating activities in the initial phase (i.e. market signals, scientific discovery, or identifying problems) informed the starting point for each different ‘ideal-type’ of innovation. Additionally, the enabling and constraining factors further demarcated different innovation models. For example, closed collaboration relied
upon mission-oriented agencies to co-analyze problems with industry-based contractors. That enabled the creation of manufactured nano-products, e.g. a more precise laser for data-communications between helicopters during combat operations. Yet, constrained the nanotechnology to initially solve only the narrowly defined problem. Broader definitions of the problem and other perspectives are excluded – the collaboration was closed to the industry-government agents involved.

4.3. Sequences and phases of nanotechnology innovation. The interviewees provided 17 general and 49 case examples for innovation sequences. As mentioned above, all but two pathways lead to commercialization and differences appear in the wide variety of actions taken to achieve commercialization. Clustering all 66 innovation sequences results in four distinct types or “mental models” (Gorman, 1999) of nanotechnology innovation. Only two of the forty-five interviewees created an alternative model, than the one provided – the “funnel model” that he learned at the Sloan Business School and other participant drew a “S-curve” model and talked about four phases along that model. Neither alternative disrupted analysis, post interview, as the six analytical components were systematically captured. The most prominent progression of activities by phase, based on the highest frequency of mentions by participants (Tab. 2), can be labeled as “linear innovation” or “technology push”: discovery, recognizing applications, proof of concept, demonstrate scalability, commercialization, and iterative innovation. This mental model of innovation aligns almost perfectly with the early innovation model suggested by Abernathy & Townsend (1975). The second most dominant model is “market pull” (von Hippel, 1988), where the market demands innovation. The third is the
“technology-transfer” model. This aligns with the idea that academic knowledge is leveraged by small private firms (run by entrepreneurs), before the technology (or company) is scaled up and distributed by large corporations (Siegel et al., 2007). The fourth is the “closed collaboration” innovation model, whereby a client (e.g., Department of Defense) seeks to solve a problem and collaborates with innovative firms to execute the solution. It is important to note that all sequences are ideal-typical and interviewees recognized iterations, dynamism and overlap between phases. And yet the ideal-type models that emerged through the narratives have clear differences in each phase of innovation, as captured by the analytical tool and described in the following section.
Table 2.2

Phase-specific Activities, Actors, Barriers, and Carriers

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
<th>Phase IV</th>
<th>Phase V</th>
<th>Phase VI</th>
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<tbody>
<tr>
<td>Initialization</td>
<td>Experimentation</td>
<td>Proof of Concept</td>
<td>Compliance</td>
<td>Commercialization</td>
<td>Endings &amp; New Beginnings</td>
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<tr>
<td>Discovery via basic research (21)</td>
<td>Recognizing application (40)</td>
<td>Proof of concept (34)</td>
<td>Demonstrate scalability (30)</td>
<td>Commercialization (40)</td>
<td>Iterative Innovation (25)</td>
</tr>
<tr>
<td>Developing new concepts (18)</td>
<td>Experimentation (16)</td>
<td>Assessing market potential (21)</td>
<td>Bring on early adopters (20)</td>
<td>Operationalize (3)</td>
<td>End-of-Life (9)</td>
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<tr>
<td>Identify problem (13)</td>
<td>Problem analysis (4)</td>
<td>Problem solving (3)</td>
<td>Test &amp; Evaluate (7)</td>
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<td>Financial Exit (3)</td>
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<tr>
<td>Identify market need (8)</td>
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<td>Mitigate new threats (3)</td>
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<tr>
<td>Entrepreneurs (30)</td>
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<td>Large Corps. (22)</td>
<td>Federal Funding (23)</td>
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<td>Entrepreneurial Constraints (19)</td>
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<td>Private Funding Failures (18)</td>
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<td></td>
<td>Corporate Barriers (18)</td>
<td>Market Failures (14)</td>
<td>Technical Risk</td>
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<td></td>
<td>Government Assistance (35)</td>
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<td>Academic Capacity (25)</td>
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<td>Technical Capacity (20)</td>
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*Note.* Analytical elements considered critical, based on high frequency of mentions by participants (number of mentions in parenthesis) in the nanotechnology innovation process in Phoenix.
**4.3.1. Phase I: Initialization.** The first phase is labeled “initialization” (similar to “research and exploration” in Robinson (2009)) in which actors set in motion endeavors to pursue nanotechnology innovation. Nanotechnology innovation is initiated through exploring phenomena and new concepts that address the nanoscale, identifying market needs, and identifying problems, usually through the lens of a specific sector (e.g., water, energy, medicinal). The tangible outcome is an initial, often unspecific and fairly vague nanotechnology application concept (often more defined by a need or a problem than by a solution). Government funding agencies, academic researchers, and industry dominate the initialization phase of the innovation process (see Table 2.2).

Primarily, academic and industry researchers with specific expertise, skills, and competence are given access to specialized equipment, owned by universities, research institutes, or corporations, and receive assistance through direct funding, tax credits, space, etc., often from government agencies. They make discoveries, develop ideas, and identifying problems, based on previous research and, at times, motivated by societal values.

“Our primary goal is trying to do fundamental science to understand what makes that nanoparticle unique or different. We come to that problem with a motivation of sustainable energy, but not with an intention to develop sustainable energy.”

(Academia / Research; no. 3)

Nanoscale scientists and engineers working in public and private organizations receive substantial funds from federal agencies, the top three being the Department of Defense, National Science Foundation, and National Institutes of Health (NSTC, 2011). Decision-
making processes (RFPs, proposal review and selection, etc.) within these agencies shape the research agenda, research prioritization, and research design of public and private research organizations accordingly.

“[NSF and NIH] are establishing research priorities and putting out topics to scientists to solve the grand challenges of the day. I am not sophisticated in debating things like research direction, who decided what, and gets researched upon. […] Program officers put out topics and calls.” (Academia / Leadership & Support; no. 2).

Alternatively, private entrepreneurs and business-oriented professionals develop new concepts, often based on identified market needs with funding enabled through private networks or federal grants, such as the small business innovation research (SBIR) and the small business technology transfer (STTR) program. This process might include changing jobs or institutional settings.

“All I had was a volt meter. But now that I was getting money from the [government agency], I had to throw in money. In my house, I built a room and bought equipment. Then, they wanted to visit the lab and it started to get real.” (Industry; no. 1)

While expertise, funding, and networks are strong enabling factors in the initialization phase, there are barriers to good ideas, such as short-term oriented problem-solving mandates, even within academic institutions.

“We have a problem. Solve the problem! If I want to get promoted this year or next year, I have to work on short-term problems and short-term solutions. There
is no effective compensation scheme […] that allows ten years to produce results.” (Academia / Leadership & Support; no. 3)

“At the university level, there are barriers that include divergent motivations for professors, who are typically the innovators. Often tenure and their professional track is measured more on publications, relative to […] patenting. […] So there is a pull away from innovation.” (Consulting Firms / Business & Legal; no. 6)

There are also more structural or background barriers that reflect the local socio-cultural context in which nanotechnology innovation in metropolitan Phoenix takes place:

“The history of successful land speculation begs the question, why would you invest in nanotechnology? Why take that risk?” (Consulting Firms / Legal & Business; no. 2)

“And that is kind of where Phoenix is today, in its evolution, comparative to the San Jose area or Boston where they have gone through this process. We have never really gotten to the point to have an exit strategy for the investors. We are still young.” (Media; no. 1)

4.3.2. Phase II: Experimentation. The same actors, those with highly specialized expertise, strong problem-solving skills, and creativity leverage all their assets to move ideas forward. They seek to refine and apply initial concepts and solution options. The tangible outcome is a refined nanotechnology application concept, at times even a prototype, which holds the promise of value. This phase orients the innovation efforts by recognizing and exploring nanotechnology applications within specific sectors (e.g. semi-
conductors) and receiving application-oriented funding and support.

Academic researchers and private entrepreneurs recognize applications of knowledge and experiment with technological ideas.

“We noticed a particular characteristic of the material we were working with. We were trying to build a sensor and we discovered it had a failure mode because of the electro-chemical processes at the nanoscale. Instead of throwing up our arms – we recognized we could use this failure mode. It could be applied in solid state memory.” (Academia / Research; no. 1).

Entrepreneurial efforts without strong institutional support and a dearth of private funding are held in tension between an individual’s capacity and limitations (Tab. 2). Entrepreneurs bootstrap and move forward, relying on themselves and their (social) networks. They work out of laboratories located in garages, in the corners of old office buildings, and equipment is rented or borrowed from larger organizations.

“We have found out how to make nano-powders differently and better. We had to experiment with plasma guns. First we had to build the gun and the collection system to capture the nanoparticles. (Industry; no. 3)

Federal research funds, university laboratories, equipment, and inexpensive graduate researchers are the primary supports for academic researchers. Yet, to receive federal funding, the funding request must align the proposed research activities to, “facilitate continued progress in nanotechnology and to encourage ready access to state-of-the-art research capabilities for accelerated commercialization efforts” (NSTC, 2012). This presents a significant barrier to pursue diversified research agendas and orients the value
proposition of nanotechnology toward commercial markets. Market failure was described as a significant barrier in this phase (Tab. 2).

“The real purpose is to connect the industry with the [academic] researcher. … What we like to see is that this is done with distinct needs in the marketplace. Which you do see happen, like you will see major players like Boeing or Raytheon. … They will actually help write topics with the agencies, calls for radio applications, space application, or this UAV [unmanned aerial vehicle] application. Let’s write a topic for that and start marching that up the technology readiness curve. (Academia / Leadership & Support; no. 2)

4.3.3. Phase III: Proof of Concept. In this phase, the intended goal is to prove the technology and markets exist and are compatible. Achieving this goal is required to move nanotechnology out of the lab. For university-initiated research this requires a transfer into private ownership. University technology transfer offices license nanotechnology (ABR, 2012), in accordance with the Bayh-Dole Act (Rosenberg & Nelson, 1994). Proving that a market exists and a return on investment will be achieved if financial commitments are made to the prototype can been called “up value science and technology findings” (Robinson, 2009).

Academic researchers and R&D staff prove technical concepts, whereas market-oriented partners prove market value.

“You start out with a team of market experts - strategic marketing team and a technology team and once you agree what you are going after you hand it to the technologists and say prove it.” (Industry; no. 3)
“If you are interested in how particles move relative to one another, you may have zero interest in sales and accounting and it is just that.” (Private investment groups; no. 1).

In this phase, individuals may change roles as the prototype is taken out of the laboratory; for example, academic researchers become entrepreneurs and attempt starting new companies. However, a lack of training, prior to this transition, creates numerous entrepreneurial constraints.

“I teach during the day, but my company is this. Everyone knows – oh that is [professor’s name removed] company” … He started a little effort, it was going to make short wavelength laser communications.” (Industry; no. 5)

For researchers at public universities, a critical step in this phase is the licensing of the nanotechnology application. Technology transfer offices leverage academic capacities, while playing multiple roles that go beyond simply transferring licenses. They coach academic researchers, run interference and negotiate contracts, file patent disclosures and applications. These activities are beneficial to some and present barriers to others.

“The tech transfer […] functions as an impediment. If you ask them, they are not. If you ask anyone else in the world, they are.” (Private investment group; no. 1)

“This is one of the breakdowns that the academic community has, it is inherent in our system. There are very few people who know and have managed from research to commercialization. So, usually you have two very different types of people working within silo-ed organizations.” (Academia / Leadership & Support; no. 3)
On the other hand, technology transfer offices may give researchers preference in licensing decisions, even if the university is offered more money by a corporate interest – which is not in line with published work on technology transfer as a mechanism for university profit (Rosenberg & Nelson, 1994; Florida, 1999).

“They [technology transfer officers] did a great job of running interference with bigger companies to help our venture out of the laboratory. They put us in the driving seat, so to speak.” (Academia / Research; no. 1)

In this phase there continues to be a high level of technical risk; i.e., malfunction or failure.

“One of the challenges of some of the areas like semi-conductors, nanotechnology … it takes huge sums of money to get over the technical risk and you still have the marketing risk.” (Consulting Firms / Legal & Business; no. 5)

Once the technology is licensed from the university it requires private investors (e.g. angel investors, venture capitalists, and institutional investors) to hire technical personal, pay for access to high-cost equipment, and test nanotechnology prototypes to ensure functionality of the initial product.

“Now that they are out of the lab, they are looking at the reality, get money or die.” (Private investment group; no. 1)

Apart from fundraising skills, particular expertise held by experienced business executives and consultants are needed to integrate laboratory prototypes into the buyer’s systematized production process. The nanotechnology prototype needs to be adapted in a way that it can plug into the socket, to fit within the pre-defined systems of production.
“If it had not been for the funding raising skills of that person we would not have been there, but we needed to get a new person on board who had a new set of skills […] to deal with the client side of things.” (Academia / Research; no. 1)

4.3.4. Phase IV: Compliance. Struggles between regulators and regulated companies; between industry standards and novel products; and between institutional buyers and technology developers best describe this phase. Tangible outcomes include receiving a notice of compliance from the regulating agency; meeting (or changing) industry standards; and scaling the manufacturing capacity to meet anticipated client-demand. Regulatory affairs departments, product engineers, insurers, and legal consultants (among others) prepare requisite forms to initiate the approval process (different between the sectors). Approval processes, while conceived of as a barrier, are also an enabling force; if your product receives approval, future profits are close at hand and protected by the very barrier the product just overcame.

When attempting to transform tested nanotechnology prototypes into mass-produced goods, the reliability and consistency standards in semi-conductors and electronics often result in technical failure. Yet, structuring a competent team of venture capitalists and corporate investors with strong technological capacities can enable success.

“We are talking $40 million. They brought in a dream team of investors and companies that contributed equipment. They brought in fabrication facilities. They are supplying engineering samples now and customer samples near the end of the year. You need to bring up the yield to the high 90 percent, so that most of your products work, you bring up the reliability by [testing environmental
conditions], and then you have qualification, which means you can hand someone a data sheet that tells the customer what the product does.” (Academia / Research; no. 1)

Federal buyers (primarily the Department of Defense) support ‘spiral innovation’ with significant investments in financial and human capital, allowing for repeated testing and evaluation cycles that push prototypes to the breaking point and beyond. ‘Spiral innovation’ is a collaborative learning process supported by a didactic relationship between nanotechnology manufacturers (private companies) and future users (defense agencies).

“From the initial prototype – we did spiral development. We spiraled through a series of exercises. After each spiral we would sit down and do an evaluation. Is it possible or not? Go think … At the completion, the [military technology] became the program of record for the Army. (Industry; no. 8)

“In our capability statement under scientific and engineering services, we have provided services in personal armor assessments, […] ballistics evaluations, explosives formulations, occupant survival systems, aircraft crash-worthy fuel systems. [The engineers] are working alongside active duty military and other military contractors.” (Industry; no. 4)

Regulatory agencies review submitted applications for approval. In the United States, while many regulations intersect with nanotechnology, no formally adopted policies (to date) explicitly address the risks unique to products containing nanotechnology (Bosso, 2010). The Food & Drug Administration (FDA) is struggling to adjust existing policies to
the complexities of nanotechnology-based drugs and devices (Koolage & Hall, 2011). Meeting FDA approval standards, which are not yet specific to nanotechnology, is a significant barrier.

“They are very small, investor-funded and so they have limited capital. They are located here in the Valley and they are sitting here having heard nothing from the FDA. And finally out of sheer frustration, they have an attorney write a letter to one of the senior FDA officials. And it basically says, I have a client that is burning $200,000 a month and we can’t get the courtesy of a response [...] The point of the story is to demonstrate the real barriers that one can have. I had that conversation this morning.” (Consulting Firm / Legal & Business; no. 5)

The renewable energy sector struggles with the well-known market barrier imposed by existing energy prices coupled with a lack of government subsidies and tax breaks (Huesemann, 2003). Government agencies, industry standards, private-public collaborations, and market barriers all constrain the product portfolio of nanotechnology.

4.3.5. Phase V: Commercialization. In this phase, large corporations drive commercialization through profitable sales and consumers expect to reap value through the use of nano-enhanced products and services (similar to “wider societal uptake” (Robinson, 2009)). The activity, operationalization, is the language used by defense contractors and government agents for military and security agencies. Large corporations perform a number of activities, under the umbrella of commercialization, including marketing, sales, manufacturing, and distribution.

“You start selling stuff, that is the good part. You have to do the sales and
marketing. Hopefully you have done that work upfront, certainly the investors have done that work. You become focused on driving down costs and hitting your sales targets. […] [Who is doing this?] Those are your legit companies, larger companies, if you are going to get something to your consumer. You need the big financial backing” (Industry; no. 5).

Citizen-consumers and institutional buyers (e.g., city administration) purchase products through commercial markets providing financial rewards, creating the pulling forces for innovation (von Hippel, 1988). Further, the commercial market is the means by which to deliver social value, as utility.

“The idea is that they would get it into the market place where it could do good as soon as possible.” (Consulting Firms/ Business & Legal; no. 1)

This phase is not free of market barriers, especially for small-medium enterprises (SMEs), even if all previous regulatory, technical, and initial market barriers have been overcome.

“If we really truly have game-changing technology that can truly upset the apple cart that gets better performance […] then you have the challenge of competing with the big boys. You have seventy-five years of experience with the previous technology and no proven cost of manufacturing the new product at full-scale commercialization. You are trying to sell someone something to […] replace the existing known solution. It has to be much better than what they are using today.” (Industry; no. 3)

Federal agencies play multiple roles; the US Department of Health and Human Services
(DHHS) is an example. DHHS houses the NIH, a top nanotechnology funder in medical research (NSTC, 2012) and the FDA, which holds responsibility for regulating all medical devices and pharmaceuticals. These two roles create an ethically contested decision-making framework (Krenik, 2005). In this phase, monitoring of approved pharmaceuticals and devices is performed through a network of medical practitioners that funnel information back to the FDA.

“In terms of the commercialization of the product, we are heavily regulated. […] This facility will supply products worldwide. The three big agencies that we have to answer to are the FDA here in the US, the MHRA in the EU and the Japanese authorities.” (Industry; no. 6)

Outside of the medical sector, there is less clarity regarding the protection of human health and the environment. Without clearly defined roles between the actors, there are some divergent perspectives on this issue.

“Unions train workers on issues of environmental health and safety.” (Consulting Firms / Business & Legal; no. 2).

“Federal regulatory agencies protect worker health and safety.” (Industry; no. 6)

Alternatively, the role of protecting human health and the environment will not be addressed by Arizona state agencies due to a moratorium on new rules, implemented via executive order (Brewer, 2011). The executive order allows state agencies to create new rules only when required by federal statute.

“We will not regulate nano, unless the feds make us.” (Government regulatory agencies; no. 1).
The executive order is justified as a means “to prevent additional and unnecessary burdens on our private sector employers [from] a regulatory explosion detrimental to job creation and retention in this State” (Brewer, 2011).

Despite evidence indicating citizens and scientists worry about nanotechnology risks (Satterfield, et al., 2009; Scheufele et al., 2007), our study did not produce specific indications about citizens’ product feedback, preferences, concerns, risk perception, or social amplification of risk in metropolitan Phoenix. Citizens are largely absent from the innovation process (as discussed below).

4.3.6. Phase VI: Endings and New Beginnings. Two clearly divergent perspectives appear in this phase. Endings include the artifact’s end-of-life, the technology is eclipsed, or a financial exit occurs (see Table 2.2). New beginnings are iterative innovations and the emergence of new ideas (starting a new innovation process through initialization). Mostly, large corporations are re-inventing products by adding features and benefits or seeking process changes that reduce manufacturing, distribution, and marketing costs to gain higher profitability.

“You take your initial concept and make it better, […] fresh, new, shiny, for next year. […] They are going to take the product a step further, there is a constant evolution of process. […] The one thing about success is that all of a sudden people are knocking on your door and asking you for things – that is the loop.” (Media; no. 1).

Market drivers support iterative innovation and facilitate a feedback and response
mechanism between customers and large corporations. And while market failures occur, this relationship enables corporations to continue to reap financial rewards and drive production. It offers consumers a limited way to enhance the features of a product.

“Two projects led to an idea in our research group to combine these ideas and build upon the concept of Chinese handcuffs. We applied that to airbag technology. Something like 70% of all deaths in side impacts are the result of head injuries. We sold that to [German Company]. (Consulting Firms / Business & Legal; no. 1)

Consumers ultimately dispose the nano-enabled products (recycled, landfilled, etc.) and the regulation of these activities is held by federal regulatory agencies. The majority of nano-enabled products are not yet designed to facilitate repair – they are designed with replacement in mind (as indicated in the iterative innovation described above).

“It is commercialized into obsolescence, right. It continues to exist until it is no longer valuable and nobody wants it, then it is sun-setted and dies and goes to nano-heaven. The intellectual property goes into the public domain.” (Consulting Firms / Legal & Business; no. 5)

This speaks to the short-term nature of the products and applications of nanotechnology. It also speaks to intellectual property as exclusively assigned to the private, not the public domain; this resonates with the dominant innovation objective, namely, commercialization driven by corporate interests.

A few service firms perform long-term operation, maintenance and repair of the artifacts that will need to perform in the environment.
“Today, now we are getting into next generation thin-film testing and this is where it gets to the nano piece. As PV evolves […] into a more sophisticated platform, they are setting up suites in the sort of nano testing area.” (Academia / Leadership & Support; no. 2)

4.4. Innovation Stakeholders. An overarching look at the constellations in the actor network of nanotechnology innovation in metropolitan Phoenix reveals important features of the current governance regime (Wiek, et al., 2007). Academic, industry, and government actors dominate nanotechnology innovation in metropolitan Phoenix (Tab. 3) – reinforcing the importance of the “triple helix” actors (Leydesdorff & Etzkowitz, 1998). The government, at the urban scale, plays various roles throughout the innovation process. City governments are critical for land development and building construction easements; zoning and permitting provided by ombudsman services; to spending significant public funds on the creation of technology incubators. Similarly, industry performs a wide array of activities from the distribution, manufacturing, and marketing of products, to the creation of product standards and reliability measurements, and they pose barriers through market domination and pricing regimes that prolong incumbent technologies. Lastly, universities perform a variety of activities from researchers bent on exploring material properties and recognizing applications to technology transfer officers weighing options for licensing agreements to executive staff pre-selecting projects submitted to federal funding agencies.

Nanotechnology in Phoenix is a closed innovation system (see Almirall & Casadesus-Masanell (2010) for a discussion of open and closed innovation). It is the exclusive
domain of expert professionals operating within product-based sectors. There are coordination efforts, but only within the sub-networks.

So I called [President of Company]. I have known [him] for quite some time.”
(Academia / Research; no. 5); “He was a really good friend.” (Industry; no. 1); “I have known her for years.” (Industry; no. 6); “It is all about the relationships.” (Government funding agency; no. 2) [All statements stem from people working on personalized medicine in Phoenix.]

Despite collaborative efforts within product-based sectors, competition is a dominant feature not only in business but also among universities, for example.

“This [collaboration] doesn’t happen because everyone is keeping their work close to their breast. Heaven forbid someone else gets your funding! We don’t necessarily tell each other what we are working on. So, [one university] could have the missing piece that [another university] needs, but there is no easy way to look that up. You just need to hope you know the right person so you can ask.”
(Consulting Firms / Business & Legal; no. 3)

Competition between different city governments in the metropolitan area is just as intense.

“You don’t talk to people in [city name] about who you are recruiting.”
(Government funding agency; no. 5); “There is no mechanism for the cities to collaborate and work together.” (Government funding agency; no. 1); “We are out competing [city] for the best jobs, the high-tech companies, we are leading.”
(Government funding agency; no. 3)
This infighting hampers the metropolis as a collective from creating the cache held by Route 128, the Research Triangle, or Silicon Valley.

Actors outside the core triple helix play passive roles in the innovation process. Consumers are marketed to and provide product feedback during commercialization and iterative innovation phases.

“[Consumers] are important, but how do you really get them involved? I honestly don’t think it is worth the effort.” (Consulting Firms / Legal & Business; no. 2)

Non-profit advocacy organizations, including labor unions and environmental groups remain widely unrecognized in the innovation process (Tab. 3). The promoters of nanotechnology feel that those opposed to technology should not be part of the innovation process, as they get in the way. This sentiment aligns with the governance regime of ‘techno-scientific promise’ (Felt, et al., 2007).

Table 2.3

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<tr>
<th>Important Actors</th>
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<th>Percentage of mentions</th>
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<tr>
<td>Industry</td>
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Table 2.3

*Dominant Actors in Phoenix*
<table>
<thead>
<tr>
<th>Actor Type</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government Agencies, Federal</td>
<td>231</td>
<td>19.2%</td>
</tr>
<tr>
<td>Federal, Funding</td>
<td>168</td>
<td>13.9%</td>
</tr>
<tr>
<td>Federal, Non-Funding</td>
<td>63</td>
<td>5.3%</td>
</tr>
<tr>
<td>Academia</td>
<td>231</td>
<td>19.2%</td>
</tr>
<tr>
<td>Private Investment Groups</td>
<td>111</td>
<td>9.2%</td>
</tr>
<tr>
<td>Consulting Firms, Business &amp; Legal</td>
<td>109</td>
<td>9.1%</td>
</tr>
<tr>
<td>Government Agencies, Urban</td>
<td>93</td>
<td>7.7%</td>
</tr>
<tr>
<td>Citizens &amp; Consumers</td>
<td>60</td>
<td>5.0%</td>
</tr>
<tr>
<td>Media</td>
<td>16</td>
<td>1.3%</td>
</tr>
<tr>
<td>Non-business Advocacy</td>
<td>9</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Organizations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,202</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Note.* Those considered important in the actor network of nanotechnology innovation in Phoenix are listed by actor type, frequency of mentions, percentage of mentions.

5. Discussion

Results show the city functions as a powerful organizing mechanism for nanotechnology activities in the first three phases of innovation and then the city’s influence diminishes thereafter. The dominant actor groups are academic, industrial, and government funding agencies (triple helix), with looser ties to other actor groups, including media and the public. The actor network is organized around activities...
including, funding, researching, and creating manufactured nanotechnology products. Yet, it is divided along product-based sectors with few cross-sector linkages. The dominant objective of innovation is to deploy profitable commercial or operational (military) products. Considerable governmental support for entrepreneurial (e.g. small business innovation research grants) and academic research through the National Nanotechnology Initiative is enabling the early phases of nanotechnology innovation. Yet, market failures (e.g. high cost manufactured nano-products) and corporate barriers (e.g. systematized production lines) are constraining the value proposition of nanotechnology in later phases.

Two models of government-initiated research illustrate contrasting approaches to nanotechnology innovation. The practice of technology-first investments reinforces a technology-push innovation model. All the while, problem-based innovation (closed collaboration) for national defense is attempting to address the societal challenges involving safety and security. Currently, nanotechnology is thought of and practiced in a closed manner that is alternatively market-based, technology transfer-oriented, technology-push (linear) or through closed collaboration. No narratives depicted more open typologies of innovation, such as, do-it-yourself or open source innovation.

This study set out to reveal key features of the current nanotechnology innovation process and governance regime in metropolitan Phoenix. The ultimate goal of the study is to contribute to the transformation of this regime to make sure that nanotechnology innovation happens in (more) anticipatory and responsible ways. To this end, we discuss the following flaws of the current regime and potential intervention points for
transformation, based on the study results and novel technology governance concepts (Schot, 2001; Renn & Roco, 2006; Wiek, et al., 2007; te Kulve & Rip, 2011); hereby, we draw in particular from the concept of anticipatory governance (Guston, 2008; Wiek, Guston, et al., 2013).

Stakeholders innovating nanotechnology leverage place-based resources such as the abundant solar radiation, the aging retiree population, the nanotechnology research community, and historical success in semi-conductors to generate profits, create employment opportunities, and deliver nanotechnology applications that outmatch other products and services. The innovation process is also uniquely challenged in Phoenix as it copes with, for instance, the cultural memory of land development; the belief that regulations are a burden to business; and fierce inter-city competition. While our study identified particularities to the place (Phoenix) and the type of technology (nanotechnology), the general structure of the nanotechnology innovation process in metropolitan Phoenix follows, in many respects, known patterns of technology development, including linear innovation and the funnel of innovation. There is novelty in the products’ functionality, but there is little evidence that nanotechnology in Phoenix currently offers novelty in its innovation process. Illustrated with our case study, we identify the following four critical features that pose challenges to the development of emerging technologies in general, and nanotechnology in Phoenix in particular (Guston, 2008; Wiek, Guston, et al., 2013).

*Lack of integration* – The actor network is divided along product-based sectors with few cross-sector linkages. Actors belonging to the same sector often describe collaborative
activities supported by evidence, including joint proposals, grants, laboratory results, patents, publications, and entrepreneurial endeavors. Actors within the same sector are often considered (potential) collaborators; actors outside the specific sector, however, seldom engaged in innovation activities. Yet, even within the same sector, a lack of ‘up-or down-stream’ collaboration can be observed.

“There are actually clinical trial companies here in Phoenix, they call me all the time. […] I never pay any attention, because that is up-stream from where I am at, I always pass them along to those up-stream from me.” (Industry; no. 6)

Opportunities for ‘knowledge spillover’ that cities foster inherently (Jacobs, 1969) are diminished by this lack of integration. Collaboration across sectors is seen as means to mutual learning, network robustness, accelerated innovation, cradle-to-cradle design, as well as to anticipating and mitigating negative social and environmental impacts (Kemp, et al., 2005; Wiek, et al., 2007; Guston, 2008; Robinson, 2009; Graedel & Allenby, 2010). The lack of ‘up- or down-stream’ collaboration is further discussed below.

*Lack of anticipation* – The innovation process does not account for unintended consequences that might negatively impact society or the environment in the future. Previous studies on nanotechnology application point to foreseeable negative impacts, such as, ethical controversy, pollution, worker accidents, and consumer safety issues (Wiek, Guston, et al., 2013). The moratorium on new regulation is intended to remove unnecessary bureaucratic burdens, fostering laissez faire capitalism in Arizona. This differs from California’s recent call-ins for selected nano-materials (CDTSC, 2010) and from the national norm to allow state agencies to retain rule-making authority to protect
public goods and interests. Suppressing rulemaking authority lessens the government’s activity in anticipating threats and protecting workers, consumers, and the environment, which is in stark contrast to principles of sustainability-oriented governance (Kemp, et al., 2005; Wiek, et al., 2007). Anticipatory governance promoting foresight, integration, and participation would be an advantageous approach to innovate emerging technologies such as nanotechnology in Phoenix.

“The biggest challenge in the technology today, is not what is the biggest win, but what is the biggest unintended consequence in the technology or what is the unintended win. […] In Arizona, you have to maintain all your wastewater within your municipal boundaries. Where [in other places] it is sent away, it goes away – you dilute into a river, you dilute into an ocean eventually that is going to have ramifications for the entire world. In Arizona it has ramification on a much quicker level. Eventually that [nanoparticle] is going to build up in your [groundwater] recharge, eventually that doesn’t go away. We don’t have enough studies to show how fast it goes away. [The city government] could be brought into it sooner in some of these advanced technologies that have societal implications, in the future or not. If they are brought in as part of that collaborative group, we can circumvent some of the problems that mankind will create themselves.” (Government funding agencies; no. 4)

Lack of public participation & civic engagement – The current regime does not allow for public engagement opportunities at early stages of the process (up-stream, mid-stream). In fact, it does not even recognize the importance of consumers (or public opinion
communicated through media outlets). There is little evidence in this study that ‘the user matters’ criterion is being addressed (Kuhlmann, 2007). Public engagement is becoming a mechanism to create transparency and accountability in science and technology policy (PytlikZillig & Tomkins, 2011). For example, California takes a proactive approach by conducting public workshops on nanotechnology development (CDTSC, 2010). In metropolitan Phoenix, there would be ample opportunity for ‘upstream’ public participation as many local innovation actors are engaged in the first three phases of innovation. This would allow the public to shape the research agenda, identifying place-based problems, and providing early feedback on application concepts and prototypes. Our study, however, indicates strong resistance and inertia, as articulated by one workshop participant.

“[Consumers] are important, but how do you really get them involved? I honestly don’t think it is worth the effort.” (Consulting Firms / Legal & Business; no. 2)

Lack of creating public value. The actor network myopically focuses on commercialization as the sole mechanism to bring value to the public. Value relies on market forces to maximize consumer utility and commercialization is the clear mechanism to realize the “economics of technoscientific promise” (Kuhlmann, 2007). The underlying assumption is that economic growth through private markets will maximize utility (benefits) for citizens and maximize profits for corporations. It is assumed that profits will be reinvested and contribute to future growth. However, there is ample evidence that market-based commercialization creates negative externalities in the form of social and environmental externalities, which are not addressed in these
assumptions (Daly & Cobb, 1994). In fact, externalities stemming from status quo commercial markets are part of the nanotechnology product portfolio (Maclurcan & Radywyl, 2011; Kimbrell, et al., 2009).

6. Conclusions

While innovation studies often seek to contribute to the continuation of technological innovation in a sector or a region (e.g., Etzkowitz, 2012), this study aspires toward a different outcome. The ultimate objective of this study is not continuation but transformation. There is novelty in the products’ functionality, ranging from solar technology to personalized medicine, but there is little evidence that nanotechnology in Phoenix offers novelty in its innovation and governance process. Actors, almost exclusively, follow preconceived mental models of innovation and governance (e.g. market-oriented or closed-collaboration). Little attention is paid to adverse effects, co-construction, or broader public value generation. These characteristics stand in stark contrast to state-of-the-art governance for emerging technology development.

Phoenix in particular, displays some significant shortcoming with adverse effects occurring over the long term, the present study aims at identify promising intervention points to transform existing governance regimes. Guiding concepts for this transformation are emerging in the concepts of sustainable and anticipatory governance (responsible innovation). The practice-oriented analytical perspective adopted in this study refers to the obvious fact that nanotechnology innovation happens through people, their decisions and actions. They act in real time and largely within a locally defined and bound network; hence, we focused on a metropolitan area. If innovation ought to happen
somewhat differently (with somewhat different decisions and actions), namely in more anticipatory and responsible ways, we need to know who is doing what (and why) along the innovation process. Our study allowed practitioners to express their understanding of nanotechnology innovation and created an inventory of the current regime for the metropolitan area of Phoenix. This also provides initial hints towards flaws and potential intervention points.

Future research is needed in four areas. First, a criteria-based assessment is required to detail and substantiate the flaws in the current nanotechnology innovation process and governance regime. Such an assessment would need to be based on a synthesis review of current normative governance concepts to provide a transparent and substantive assessment base (Renn & Roco, 2006; Wiek, et al., 2007). Second, a systematic participatory exploration is needed on which of the analyzed actors, activities, etc. along the innovation process would be conducive to introducing good governance practices, techniques for anticipation, sustainability principles, and so forth. For example, federal funding agencies are drafting and distributing RFPs, reviewing, approving and rejecting proposals, etc., and thus, they significantly shape nanotechnology innovation in a particular way. Considering current increase of sustainability-oriented programs and initiatives in federal research funding agencies (NSF, EPA, NIH), it seems to become a promising intervention point that government agencies would do these activities differently; e.g., including other guidelines in the RFPs; apply different criteria in the review process; do extended reviews (with stakeholder involvement); etc. Third, transformational research is needed that engages innovation actors in their environments
(through participant observation and engagement) suggesting and exploring such alternative action schemes (Fisher & Wiek, in prep). Fourth and final, comparable studies are needed to overcome the limitations of a single case study on metropolitan Phoenix and to tease out generic insights in all three streams, i.e., analyzing, assessing, and transforming the current innovation processes and governance regimes.
Chapter 3

Responsibilities in Innovating Nanotechnology

1. Introduction

Innovations in nanotechnology promise to revolutionize construction, energy, transportation, medical, electronics, and other major economic sectors (Roco, Mirkin & Hersam, 2010). The innovation process largely follows the dominant model of delivering value via commercial markets and privatized goods (Foley & Wiek in prep; MacLuran & Radwyl, 2010). Alternative innovation models, including open-source innovation and social entrepreneurship, are still marginal. Following neo-classical economics the assumption is that commercialization of nano-enhanced products creates a trickle-down effect that provides benefits to society at large. Yet, studies show that this often does not happen in an equitable fashion (Pidgeon et al., 2008; Cozzens & Wetmore, 2011). In fact, the commercialization model of innovation brings into play a range of potential negative effects, including threats to public health and the environment, in addition to issues of inequity and injustice (Daly & Cobb, 1989; Wiek et al., 2013; Linkov & Seager, 2011; Breggin & Carothers, 2006). An example is the expanded commercialization of nano-enabled electronics and anti-microbial wear both contributing to an increasing rate of manufactured nano-particles released to environmental (i.e. water, air, and soil systems) and exposed to humans (i.e. workplace environments, direct consumer contact, and into disposal outlets) systems.

While negative effects loom on the horizon, only a limited set of formal policies, regulations, and standards offer guidance to the diverse stakeholders engaged in
nanotechnology innovation (Mallory, 2011; Bosso, 2010; Kimbrell et al., 2009; Linkov et al., 2009). We consider here everyone with a role in the nanotechnology innovation process, including those directly affected by nanotechnology innovation as a stakeholder.

Government’s capacity for maintaining environmental, health, and safety compliance or addressing future risks of nanotechnology and other emerging technologies has been called into question (Bosso et al., 2011). Currently, few policy memos and documents have been issued by U.S. federal, state, or municipal agencies that address handling nanotechnology (Roco, Harthorn, et al., 2011; Conley, 2012). Hence, many stakeholders are unsure of how to innovate nanotechnology responsibly (Rip & Shelley-Egan, 2010). In response to this challenge, normative frameworks under the guiding idea of responsible innovation have been developed (Roco, Harthorn, et al., 2011; Von Schomberg, 2013), including, among others, risk governance, sustainability-oriented governance and anticipatory governance of nanotechnology. Their intention is to mitigate, anticipate, and/or ameliorate potentially negative consequences of nanotechnology and to offer novel ways of governing such technologies:

(i) **Risk Governance** joins risk-benefit evaluations with resolving risk–risk trade-offs, while considering the societal and cultural context, as well as broader implications of nanotechnology (Renn & Roco, 2006; Roco et al., 2011)

(ii) **Sustainability-oriented Governance** calls for a balanced pursuit of economic development, environmental quality, and social justice in the long term when innovating nanotechnology (Daly & Cobb, 1989; Kemp et al., 2005; Wiek et al., 2007)

(iii) **Anticipatory Governance** is a collaborative decision-making process
facilitating nanotechnology innovation through foresight, knowledge integration of natural and social sciences, and engagement among citizens, artists, engineers, scientists, policy-makers, and corporations, among others (Karinen & Guston, 2010; Wiek, Guston, et al., 2013).

These different streams of literature have been articulated separately due to disciplinary boundaries. Professionals in environmental health and safety (EHS) focus on risk governance to evaluate and mitigate potential and realized hazards; sustainability scholars have focused on normative principles to provide societal guidance in the long-term; and social scientists involved in science, technology, and society studies have develop the concept of anticipatory governance. In addition, these concepts are often unheeded in nanotechnology innovation processes because they lack full operationalization, i.e., translating guidelines into stakeholder-specific responsibilities (Wiek et al. 2007; Wiek & Larson, 2012). The latter is critical because without connecting normative responsibilities to stakeholders, responsibilities might not get acknowledged and implemented.

The goal of this chapter is to harvest and consolidate the diverse insights across these different governance approaches and to make them applicable to nanotechnology innovations as they are happening. The specific objectives are threefold:

1. Synthesize literature across disciplines toward an integrated normative concept of responsibilities in nanotechnology innovation;

2. Operationalize responsibilities for stakeholders within distinct phases of the innovation process and to make them tangible, negotiable, and applicable;
3. Apply the operationalized concepts to a current governance regime to identify strengths, weaknesses, and gaps.

Within the empirical study, we focus on nanotechnology governance in metropolitan Phoenix and address three research questions:

(i) Which stakeholders are currently engaged in the nanotechnology innovation process?

(ii) What responsibilities do stakeholder groups assign to themselves and to others?

(iii) Do these responsibilities align or contrast with the synthesized set of normative responsibilities?

Recent studies call for investigating existing governance regimes and addressing concerns about the pace and scale of nanotechnology development in the absence of formal regulations (Wintle et al., 2007; Kimbrell, 2009). The present study integrates selected contributions on advanced forms of nanotechnology governance into an operational framework and shows how it can serve for evaluating or designing governance regimes striving for the responsible innovation of nanotechnology.

2. Literature Review

The first step was to synthesize literature on normative responsibilities in innovation and then operationalized this set of responsibilities for diverse stakeholder groups governing nanotechnology, employing the stakeholder categories offered by Wiek et al. (2007). The literature synthesis is based on the review of numerous sources.
detailing the three selected governance approaches (e.g., Daly & Cobb, 1989; Kemp et al., 2005; Fisher et al., 2006; Renn & Roco, 2006; Wiek et al., 2007; Guston, 2008; Karinen & Guston, 2010; Roco et al., 2011; Wiek, Guston, et al., 2013). Literature was reviewed with respect to relevant governance responsibilities (e.g., precautionary management of risks) and/or stakeholder groups (e.g., insurance companies). Based on these initial reviews, the synthesis linked normative responsibilities to specific stakeholder groups. Finally, the responsibilities were aligned with distinct phases of the innovation process, following recent innovation process models (Robinson, 2009; Foley & Wiek, in prep).

3. A Set of Normative Responsibilities for Nanotechnology Innovation

The literature synthesis yielded a set of thirty-three normative responsibilities assigned to stakeholders who operate within discrete phases or across several phases of the nanotechnology innovation process (Tab. 1). Risk governance, sustainability-oriented governance, and anticipatory governance provide distinct, yet complementary contributions to this compilation. Convergence is prominent in many instances, for instance, the plea for an adaptive regulatory framework (Tab. 1, H5). The compilation is not, however, without tensions. For example, Philbrick (2010, pp. 1717) asserts the importance of stakeholders evaluating and selecting “risk management strategies,” while Von Schomberg (2012) instead suggests pursuing “social and ecological benefits and not just mitigating harms or risks” (Tab. 1, H6). These differences hint to the broader philosophical or ideological background of the proposed responsibilities. It would go beyond the scope of this study to address and reconcile these tensions. While present in
the compilation, they do not hamper the overall applicability. In fact, the compilation allows to be flexibly adopted, depending on the specific broader philosophical or ideological background.
Table 3.1

*Synthesized Set of Normative Responsibilities for Nanotechnology Innovation*

<table>
<thead>
<tr>
<th>Normative Responsibilities</th>
<th>Stakeholders</th>
<th>Sources</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>i.</em> Support nanotechnology innovation through funding, taxation policy, and other mechanisms in a manner that offers opportunity on the basis of merit and need.</td>
<td>Government funding and support agencies, Non-governmental organizations</td>
<td>Cozzens, 2011; Gibson, 2006; Robinson, 2009</td>
<td>A.</td>
</tr>
<tr>
<td><em>ii.</em> Consider equity explicitly in the decision-making process when awarding incentives.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support the exploration of environmental health, and safety (EHS) and ethical, legal, and social implications (ELSI) by integrating social and risk-oriented sciences in all nanoscale science and engineering (NSE) programs funding and support awards.</td>
<td>Government funding and support agencies, Academic research institutions, Industry</td>
<td>Fisher, et al., 2006; Guston, 2008; Marquis et al., 2011; Renn &amp; Roco, 2006; Robinson, 2009</td>
<td>A.</td>
</tr>
</tbody>
</table>
i. Conduct public outreach and engagement as part of the 21st century science policy.

ii. Engage all affected stakeholders in deliberative processes on issues pertinent to both nanotechnology innovation and the represented communities in an effort to produce a collective understanding on how to interpret the situation and how to design procedures that legitimate binding decisions and acknowledging trade-offs.

Understand broader public perceptions through surveys that assess potential social responses to nanotechnology changes.

Government funding and support agencies, Academic research institutions, Industry, Non-governmental organizations

Chittenden, 2011;  Cobb 2011; Cozzens, 2011; Grunwald, 2004; Renn & Roco, 2006; Wiek et al., 2007

Government funding and support agencies, Academic research institutions

Owen et al., 2009; Renn & Roco, 2006; Robinson, 2009
Ensure future generations are afforded an equal opportunity for benefits and freedom from risks that may result from nanotechnology innovation through long-term planning. Consider using tools such as – road mapping, visioning, and scenario planning.

Publically disclose and disseminate all risk analysis and risk assessment data in both technical and non-technical language to create an atmosphere of open communication and trust about the potential risks and benefits of nanotechnology applications.
Plan and organize around science districts focused on leveraging regional assets, while becoming centers of excellence and innovation.

Government funding and support agencies, Industry, Academic research institutions, Non-governmental organizations

Gibson, 2006; Robinson, 2009

Address materials and energy impacts associated with modeled or physical prototype to ensure that socio-ecological integrity (such as toxicology studies, natural resources demand, and energy demand) is considered explicitly before moving forward. Develop tools like anticipatory life cycle analysis to understand the potential impacts that may result if prototypes are scaled to meet commercial demands.

Government funding and support agencies, Government regulatory agencies, Academic research institutions, Industry, Non-governmental organizations

Gibson, 2006; Robinson, 2009; Wender et al., 2012; Wiek et al., 2007
Sponsor NSE activities benefiting both social and ecological systems, such as pro-poor technologies and ‘green’ technologies that are resource or energy efficient.

Once a prototype is modeled (or built), assess the risks and benefits of the novel nanotechnology to humans and the environment by using foresight methods (and historical lessons) to engage stakeholders and build capacity to consider unintended consequences.

i. Practice precaution and operate ‘as if’ the novel nanotechnology is dangerous while impartially exploring risks (without bias toward interested groups) through tools such as risk-benefit analysis and multi-criteria decision-making.

ii. Enact regulations that position nanotechnology ‘as if’ dangerous, unless proven otherwise.

Government funding and support agencies, Industry, Non-governmental organizations

Cozzens, 2011; Gibson, 2006

Government funding and support agencies, Industry, Non-governmental organizations

Guston, 2008; Renn & Roco, 2006; Wiek et al., 2007

Government funding and support agencies, Academic research institutions, Industry, Non-governmental organizations.

Philbrick, 2010; Renn & Roco, 2006; Wiek et al., 2007

Insurers
Align promotion and tenure packages to recognize value of public engagement and problem-oriented innovations in science and technology that provision social or ecological values through non-markets structures.

Support efforts that demonstrate means to improve or restore socio-ecological system functions through funding, competitions, taxation, land use policy, and other available mechanisms.

Conduct tests that demonstrate that socio-ecological system integrity will not be destabilized through the release or introduction of nanotechnology in full production, use, and at the end-of-life. Use measures of ecotoxicity, human health, and net energy analysis, to model future impacts.
<table>
<thead>
<tr>
<th>i. Evaluate future market and technical risks (ranging from consumer acceptance to worker health and safety) using near-term forecasting and scenario tools coupled with knowledge and perception of risks to eliminate immediate and longer-term impacts.</th>
<th>Industry, Non-governmental organizations</th>
<th>Gibson, 2006; Renn &amp; Roco, 2006; Robinson, 2009; Wiek et al., 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>ii. Transparently report findings.</td>
<td>Industry, Non-governmental organizations</td>
<td>Gibson, 2006; Kimbrell, 2009; ObservatoryNANO, 2012; Renn &amp; Roco, 2006; Robinson, 2009</td>
</tr>
<tr>
<td>Construct an active management plan to address issues of risk (technical and market based) ensuring worker, consumer, and financial risks are adequately mitigated. Plan should include indicators that provide feedback on the efficacy of and show gaps in the program.</td>
<td>Industry, Non-governmental organizations</td>
<td>Gibson, 2006; Kimbrell, 2009; ObservatoryNANO, 2012; Renn &amp; Roco, 2006; Robinson, 2009</td>
</tr>
<tr>
<td>Implement corporate policies to address safety and technical concerns through the development of best practices and lesson learned (from success and failure) and share those stories to foster transparency and collective learning.</td>
<td>Industry, Non-governmental organizations</td>
<td>Gibson, 2006; Kimbrell, 2009; ObservatoryNANO, 2012; Renn &amp; Roco, 2006; Robinson, 2009</td>
</tr>
</tbody>
</table>
Mitigate risks prior to market entry through regulatory, standards, and insurance mechanisms that are specific to nanotechnology and adapt to knowledge provisioned through a network of researchers attuned to EHS & ELSI findings. When possible, build upon existing regulatory, standards, and insurance-based risk tolerances.

| Pressure companies to create products that reduce social and environmental impacts (e.g. energy, materials, and environmental degradation, and labor equity) through government incentives, consumer choice, and corporate competition. |
|---|---|---|---|
| Ensure access to livelihood opportunities in nanotechnology manufacturing by training a diverse community in the requisite skills to equalize the distribution of earning (demographically and geographically), while maintaining profitability. |
| Industry, Government, regulatory agencies, Insurers, Academic research institutions |
| Gibson, 2006; Kimbrell, 2009; Owen et al., 2009; Philbrick, 2010; Renn & Roco, 2006; Robinson, 2009 |
| Government funding and support agencies, Industry, Non-governmental organizations |
| Gibson, 2006; Renn & Roco, 2006 |
| Cozzens, 2011; Gibson, 2006; Wiek et al., 2007 |
Provision benefits through commercial markets to consumers, while seeking to overcome equity barriers (e.g. poverty).

Create user-based knowledge networks to facilitate shared learning about benefits, best practices, and unintended consequences. Feed shared learning back into innovation process to mitigate long-term impacts through real-time feedback mechanisms.

Ensure worker health and safety is protected through corporate policy, worker practices, and government regulations.

Government funding and support agencies, Industry, Non-governmental organizations

Non-governmental organizations, Industry

Non-governmental organizations, Industry

Non-governmental organizations, Industry, Government regulatory agencies

Gibson, 2006; Renn & C.3

Roco, 2006

Roco, 2006

Breggin & Carothers, C.5

2006
Afford customers the choice to not purchase nano-containing products through labeling that provisions information on known risks.

Facilitate open and continuous forums for information sharing between users, regulatory, corporate, and public interests to enhance reflexivity through knowledge networks and shared learning.

Temper risk by taking two actions: *i.* create a CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) style regulation specific to nanotechnology by investing tax revenue into prevention, mitigation, and future remediation efforts; *ii.* do not provide backstop insurance as a financial 'fail safe' against catastrophic loses.
Keep options for future development open by maintaining open-ended processes that reinforce an adaptive approach to problem solving. Avoid lock-in to sub-optimal solutions.

Establish and maintain a collaborative forum to communicate transparently the knowledge, rules, and responsibilities that comprise the governance network and reflect upon this periodically to understand the current outcomes and seek to transform them into more positive outcomes.
Develop a regional reporting scheme to exchange information on the quantities, risks, and mitigation measures about all nanotechnology products (and nanotechnology-intermediaries). This would amend the current community-right-to-know and toxics release inventory.

Organize an international oversight board to advise, train, and harmonize global knowledge, education, and policies on nanotechnology. Focus on issues of convergence and communicating findings to national and regional decision-making bodies.
Review existing regulatory schemes and understand how nanotechnology is currently regulated and identify opportunities to amend existing policies to nanoscale issues, rather than creating entirely new regulations.

<table>
<thead>
<tr>
<th>Enact an adaptive regulatory framework that can flexibly move from 'soft law' to 'command and control' policies based on iterative consultation by taking an active management role in constructing rules and processes that account for trade-offs in a manner guided by a shared vision of nanotechnology innovation.</th>
</tr>
</thead>
</table>

| Government regulatory agencies, Non-governmental organizations, Academic research institutions, Industry, Academic research institutions, Industry, Government regulatory agencies | Brown, 2009; Koolage & Hall, 2011; Renn & 4 Roco, 2006 |
| Government funding and support agencies, Non-governmental organizations, Academic research institutions, Industry, Government regulatory agencies | Brown, 2009; Faucheux & Nicolai, 1998; Ramachandran et al., 2011; Kemp, et al., 2005 |
Secure mankind’s continued existence through an embedded relationship with the Earth by pursuing social and ecological benefits and not just mitigating harms or risks.

Construct and maintain forums for engagements between citizens, diverse sectors of the public, and traditional science and technology stakeholders occupied in nanotechnology innovation that focus on equal standing and mutual learning activities.

| Secure mankind’s continued existence through an embedded relationship with the Earth by pursuing social and ecological benefits and not just mitigating harms or risks. | All stakeholders | Gibson, 2006; Grunwald, 2004; Von Schomberg, 2012; Wiek et al., 2007 |
| Construct and maintain forums for engagements between citizens, diverse sectors of the public, and traditional science and technology stakeholders occupied in nanotechnology innovation that focus on equal standing and mutual learning activities. | Government funding and support agencies, Academic research institutions, Non-governmental organizations | Guston, 2008; Ramachandran et al., 2011; Kemp et al., 2005 |

Note. Responsibilities are grouped by phase of the innovation process (first column) with stakeholders assigned (third column). Each responsibility is identifiable through a code (ID) for discussion and evaluative purposes.
The normative responsibilities comprising the framework are stakeholder-oriented in two directions. First, principles are instructions to stakeholders that are or should be engaged in nanotechnology innovation. An example is S2, which states that government regulators, insurers, and private corporations ought to “conduct tests that demonstrate that socio-ecological system integrity will not be destabilized through the release or introduction of nanotechnology in full production, use, and at the end-of-life.” Secondly, the normative responsibilities are objectives to guide the process toward responsible innovation of nanotechnology. Such an objective is exemplified in P3: “Once a prototype is modeled (or built), assess the risks and benefits of the novel nanotechnology to humans and the environment by using foresight methods (and historical lessons) to engage stakeholders and build capacity to consider unintended consequences.” The framework offers normative responsibilities as an additional set of gating questions to augment standard technology assessments (i.e., feasibility and profitability).

4. Case Study: Nanotechnology Governance in Metropolitan Phoenix

We explore the applicability of the synthesized framework with an empirical case study from the metropolitan area of Phoenix.

4.1. Case profile. The case study focuses on metropolitan Phoenix, for comparisons with other urban innovation clusters. Phoenix ranked in the top thirty U.S. cities for patenting and publications of nanotechnology (Youtie & Shapira, 2011). More recently, Phoenix ranked 18th is a national study of patenting activities only (Rothwell, Lobo, et al., 2013). Phoenix is linked to other cities, but patent activity indicates that metropolitan Phoenix is largely independent from neighboring cities, including Tucson,
Los Angeles, and Albuquerque (Foley & Wiek, in prep). As a late entrant innovation cluster, Phoenix is focused on specific nanotechnology industry sectors including renewable energy, personalized medicine, electronics and semi-conductors, aerospace and defense, automobile enhancements, and water decontamination (Foley & Wiek, in prep).

Metropolitan Phoenix has 3.8 million residences (US Census, 2010) and contains city, county and state levels of government. Hundreds of researchers, entrepreneurs, and industrial stakeholders are engaged in the nanotechnology innovation process, as well as, a network of technology-focused media, insurers, lawyers, business consultants, and advocacy organizations.

4.2. Research design. The case study adopts, integrates, and further develops research designs from previous governance studies (Wiek et al., 2007; Wiek & Larson, 2012). It draws upon expert interviews as the primary data set. Prior to sampling, 365 stakeholder organizations that work directly and indirectly with nanotechnology were identified and cataloged (Tab. 2). Organizations included university research centers, business units, local subsidiaries of national organizations, and local outlets affiliated with regional or national media. Out of the 365 identified organizations a sample population of 143 organizations was randomly selected. The distribution of participants’ roles reflects the distribution within the overall sample. Individuals working in senior management levels were targeted for interviews, including chief executive officers, vice presidents, general managers, and university professors, to ensure that broad perspectives would be captured in the interviews. Interviews with 45 individuals across the nine
stakeholder groups were conducted and the response rate ranged from 24% to 66% by stakeholder group.

Table 3.2

**Sampling Summary**

<table>
<thead>
<tr>
<th>Stakeholder Categories</th>
<th>Total Population</th>
<th>Sample Population</th>
<th>Interviews Completed</th>
<th>Response Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry – directly working on nanotechnology</td>
<td>80</td>
<td>37</td>
<td>9</td>
<td>24%</td>
</tr>
<tr>
<td>Consultants – supporting industry with business and legal advice</td>
<td>50</td>
<td>21</td>
<td>6</td>
<td>29%</td>
</tr>
<tr>
<td>Insurers – providing industry with liability coverage</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>33%</td>
</tr>
<tr>
<td>Investors – private funding of industry and academic research institutions</td>
<td>30</td>
<td>7</td>
<td>3</td>
<td>43%</td>
</tr>
<tr>
<td>Academic Research institutions – nanoscale scientists and engineers and academic leadership and support</td>
<td>100</td>
<td>45</td>
<td>14</td>
<td>31%</td>
</tr>
</tbody>
</table>
Interviewees were asked to identify key stakeholders involved in nanotechnology innovation in Phoenix and elsewhere. For example, federal funding agencies were mentioned and while they are not located in Phoenix, they play an active role in funding nanoscale science and engineering in Phoenix. Data was aggregated and normalized for the actor network analysis.

Interviewees stated their self-perceived responsibilities in the nanotechnology innovation process and then assigned responsibilities to every other stakeholder they had
identified earlier. Quantitative methods that measure collective responsibility with a stakeholder network are neither well established or without limitations (Whalan, 2012). Thereby, the methods for analyzing and evaluating the results are described in some detail here. In identifying responsibilities, interviewees were not led by questions about risk governance, sustainability-oriented, or anticipatory governance. The interviews resulted in 965 unique responsibilities aligning with the nine identified stakeholder roles.

Data analysis commenced by clustering the statements. In a two-day working session with an interdisciplinary research team the compiled responsibilities were analyzed with a coding scheme. First, statements were evaluated for explicitly stating values, or absent of value and purely functional tasks; those statements that were evaluated as expressing value were then assessed for explicit mention of non-market-oriented values (NC), such as “bridge gap between public and decision-makers to affect change” (Government regulatory agencies no. 2). All others were deemed to express market-oriented values (C), for example, “provide tax breaks to technology companies” (Industry no. 1).

Responsibilities that expressed functional task and market-oriented values (C) were combined, following the argument that functional responsibilities are aligned with orientation of regional innovation system as toward commercialization (Foley & Wiek, in prep). Statements that expressed non-market-oriented values (NC) were then coded as follows: Responsibilities were bifurcated between societally-oriented (S) values only and those that expressed socio-ecological (S/E) values. The differentiation between those two value sets was based on the difference between entirely human-focused positions and those expressing complex interactions between humans and the environment. The coding
resulted in a proportion between 0 and 1 for each of the three categories (C, S, S/E).

In the final step the responsibilities that expressed socially-oriented and socio-ecological value were aligned with the normative responsibilities synthesized before (see Section 3 above). The results were normalized by the total number of interviewees (n=45).

To evaluate the actor network, stakeholder groups that demonstrate two or fewer connections to other stakeholder groups are considered insufficiently connected to the network. Evaluation of the first tier of the coded responsibilities relies on the triple bottom line concept of sustainability, which weights economic, social, and ecological aspects equally (Hacking & Guthrie, 2008). An evaluation of the alignment between elicited and normative responsibilities relies on three criteria: (i) presence or absence of alignment; (ii) if a normative responsibilities is mentioned at least once or more than once per interview a weighed score of $\geq 1.0$ is observed and the normative responsibility is classified as universally acknowledged by all stakeholders; and (iii) present, but not universally acknowledged by all stakeholders.

4.3. Case Study Results.

Connectivity in the Agent Network of Nanotechnology Governance in Phoenix

The agent network of nanotechnology governance in metropolitan Phoenix depicts the level of mutual recognition between stakeholder groups (Tab. 3 and Fig. 1). A high recognition for government funding and support agencies, industry, and academic research institutions is clear. This emphasizes a cultural affinity within Phoenix for funding, researching, and creating nanotechnology products. Each of the nine
stakeholder groups analyzed is represented and exhibits at least one connection into the network. Four key stakeholders are not sufficiently recognized in the network (i.e. two or fewer connections to other stakeholders). Government regulatory agencies and insurers are the groups with roles that mitigate, ameliorate, or contest technological innovation on the grounds of liability and risk. The other two isolated stakeholders, the media and NGOs, are key links to citizens by providing information to and advocating for public interests.

*Figure 3.1.* Agent network of nanotechnology in metropolitan Phoenix. Circle sizes represent number of reciprocal mentions by stakeholder-category, line sizes represent number of stakeholders mentioning each other with a cut-off of less than one (<1.0). Figure is based on the dataset from Table 3, below.
Table 3.3

**Nanotechnology Agent Network in metropolitan Phoenix (and beyond)**

<table>
<thead>
<tr>
<th>Actor</th>
<th>Activity</th>
<th>Ind (n=9)</th>
<th>Con (n=6)</th>
<th>Ins (n=1)</th>
<th>Inv (n=3)</th>
<th>Res (n=14)</th>
<th>Gov (n=2)</th>
<th>Ref (n=6)</th>
<th>NGO (n=2)</th>
<th>Med (n=2)</th>
<th>Summ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ind (n=9)</td>
<td>2.7</td>
<td>1.4</td>
<td>0.1</td>
<td>0.7</td>
<td>1.1</td>
<td>0.8</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>Con (n=6)</td>
<td>2.2</td>
<td>1.7</td>
<td>0.0</td>
<td>1.3</td>
<td>1.0</td>
<td>0.3</td>
<td>3.0</td>
<td>0.2</td>
<td>0.2</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Ins (n=1)</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Inv (n=3)</td>
<td>4.0</td>
<td>2.0</td>
<td>0.0</td>
<td>2.7</td>
<td>1.0</td>
<td>1.0</td>
<td>2.3</td>
<td>0.0</td>
<td>0.0</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>Res (n=14)</td>
<td>2.3</td>
<td>1.0</td>
<td>0.1</td>
<td>1.2</td>
<td>1.1</td>
<td>0.4</td>
<td>2.2</td>
<td>0.0</td>
<td>0.5</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>Gov (n=2)</td>
<td>1.5</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5</td>
<td>2.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Ref (n=6)</td>
<td>3.3</td>
<td>0.2</td>
<td>0.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.0</td>
<td>4.3</td>
<td>0.0</td>
<td>0.0</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>NGO (n=2)</td>
<td>2.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>4.5</td>
<td>1.0</td>
<td>1.0</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Med (n=2)</td>
<td>1.5</td>
<td>1.5</td>
<td>0.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.0</td>
<td>6.5</td>
<td>0.0</td>
<td>1.0</td>
<td>13.5</td>
<td></td>
</tr>
</tbody>
</table>

| Passivity | Summ | 21.4 | 10.3 | 1.2 | 12.8 | 7.7 | 5.0 | 26.2 | 2.2 | 3.6 |

**Note.** Data are standardized by averaging the number of stakeholders mentioned (aggregated to the level of agent categories). Stakeholders from the left mentioned agents at the top (n=45). Key: Ind = Industry, Con = Consultants, Ins = Insurers, Inv = Investors, Res = Academic research institutes, Gov = Government regulatory agencies, Ref = Government funding & support agencies, NGO = Non-Government Organizations, Med = Media.

**Triple Bottom Line Appraisal of Responsibilities in Phoenix**

The elicited statements reflect that economic values are highly dominant and overshadow societally-oriented values and socio-ecological values across the stakeholder groups (Tab. 4). The overall goal of nanotechnology innovation is expressed as commercialization (Foley & Wiek, in prep) and the majority of the responsibilities throughout every phase of the innovation process align with that goal.
Table 3.4

Responsibilities Assigned to the Top Five Stakeholder Groups Mentioned

<table>
<thead>
<tr>
<th>Organization</th>
<th>General Values</th>
<th>Normative Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Academic research institutions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understand application of knowledge to human challenges or market gap</td>
<td>S A2, A.3.ii, P2, S1</td>
<td>17</td>
</tr>
<tr>
<td>Discovery (through basic research)</td>
<td>C</td>
<td>15</td>
</tr>
<tr>
<td>Conduct Research (through experimentation)</td>
<td>C</td>
<td>9</td>
</tr>
<tr>
<td>Proceed with early technology development &amp; become entrepreneurs</td>
<td>C</td>
<td>7</td>
</tr>
<tr>
<td>Communicate (through publications and presentations)</td>
<td>S A6, S.3.ii, PC1, H1</td>
<td>3</td>
</tr>
</tbody>
</table>

**Government funding and support agencies**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Funding Projects</td>
<td>C</td>
<td>22</td>
</tr>
<tr>
<td>Define research agenda</td>
<td>C</td>
<td>16</td>
</tr>
<tr>
<td>Evaluate potential solutions &amp; create incentives to redefine markets</td>
<td>S A.1.i, P2, S1, C1</td>
<td>6</td>
</tr>
<tr>
<td>Oversight of grants</td>
<td>C</td>
<td>4</td>
</tr>
<tr>
<td>Foresee unintended consequences of technology in localized contexts</td>
<td>SE PC3, H1</td>
<td>3</td>
</tr>
</tbody>
</table>
### Industry

Create idea and take as far as possible towards commercialization  
Conduct research and development of products that have market value  
Manufacturing nano-enabled products  
Creating demand through value-added products, marketing and selling  
Scaling products to commercialization (testing & evaluation along way)  
Commit to innovation with resources (expertise, finances, and demand)  
Forming strategic partnerships  
Create radical (or novel) innovation  
Foresee unintended consequences of technology in localized contexts

<table>
<thead>
<tr>
<th>Responsibility</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create idea and take as far as possible towards commercialization</td>
<td>C 17</td>
</tr>
<tr>
<td>Conduct research and development of products that have market value</td>
<td>C 12</td>
</tr>
<tr>
<td>Manufacturing nano-enabled products</td>
<td>C 10</td>
</tr>
<tr>
<td>Creating demand through value-added products, marketing and selling</td>
<td>C 9</td>
</tr>
<tr>
<td>Scaling products to commercialization (testing &amp; evaluation along way)</td>
<td>C 9</td>
</tr>
<tr>
<td>Commit to innovation with resources (expertise, finances, and demand)</td>
<td>C 8</td>
</tr>
<tr>
<td>Forming strategic partnerships</td>
<td>C 6</td>
</tr>
<tr>
<td>Create radical (or novel) innovation</td>
<td>S PC3 5</td>
</tr>
<tr>
<td>Foresee unintended consequences of technology in localized contexts</td>
<td>SE S2, S3, S4, S5, PC3 4</td>
</tr>
</tbody>
</table>

### Investors

Funding projects  
Selecting investments  
Oversight and Executive Management

<table>
<thead>
<tr>
<th>Responsibility</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funding projects</td>
<td>C 21</td>
</tr>
<tr>
<td>Selecting investments</td>
<td>C 19</td>
</tr>
<tr>
<td>Oversight and Executive Management</td>
<td>C 10</td>
</tr>
</tbody>
</table>

*Note. The left column contains the elicited responsibilities by group. The next column indicates general values: market-oriented/commercial (C), Societally-oriented (S), or*
socio-ecological-oriented (SE). The next column indicates links to the normative responsibilities. The far right column lists the total frequency (n) of mentions by interviewees.

Economic values accounted for 86.0% of the total identified responsibilities with (+/-) 3.3% maximum proportional range between the coding teams (Fig. 2). The remaining responsibilities were bifurcated between societally-oriented values which occurred 8.5% and socio-ecological values occurring 5.5% with a maximum proportional range of 3.7% and 2.4%, respectively.

**Figure 3.2.** Responsibilities aligned with the triple bottom line concept of sustainability. The aggregated number of responsibilities classified along each axis is expressed as a whole number, while the percentage represents the mean proportion between the three research teams. Within the parenthesis is the maximum proportional range from the mean.
The state of responsible nanotechnology innovation in Phoenix

Eight responsibilities (A.1.ii, P.4, C.2, C.3, C.6, PC.2, H.3, and H.6) out of the thirty-three normative responsibilities (shown in Tab. 1) are absent from the interviewees’ statements on responsibility. For example, the normative responsibility, “consider equity explicitly in the decision-making process when awarding incentives” does not align with any of the interviewees’ statements. Additionally, no one mentioned “practicing precaution prior to having a full understanding of the risks of a specific nanotechnology.”

The three normative responsibilities A.2, P.2, and S.1) had the highest frequency of alignment with interviewees’ statements; however, not a single normative responsibility was universally expressed (universal = \( \geq 1.0 \)) by the stakeholder network (Fig. 3). This means that the interviewee did not express a single normative responsibility at least once or more frequently. The result is that not a single normative responsibility is held as a collective responsibility. Thus, the stakeholder network does not universally acknowledge any one of the thirty-three normative responsibilities.

More normative responsibilities aligned with interviewees’ statements in the ‘upstream’ innovation phases – *initialization and experimentation; proof of concept* (average normalized score of 0.29). Fewer interviewee statements align with ‘downstream’ phases (0.18). This result indicates that while no normative responsibility is universal, there is greater attention paid to normative responsibilities in the early phases of innovation. Therefore, ‘upstream’ responsibilities are understood by a greater number of people within metropolitan Phoenix. This may suggest an imbalance or
disconnect between regional and global stakeholders in the nanotechnology innovation system. Alternatively, the attention to ‘upstream’ responsibilities reinforces the concept that nanotechnology innovation originates from the urban environment and then moves out to national and global scales.

Figure 3.3. Alignment of elicited responsibilities and normative responsibilities. The code along the left hand side of the figure directly corresponds to the far right hand column in Table 1. Responsibilities could be categorized into more than one group. The results depict responsibilities that are not aligned with market-oriented values. Results
were normalized by the total number of interviewees (45).

5. Discussion

The stakeholder network is attuned to organizations that are funding, researching, and creating nanotechnologies and displays a lack of connectivity (<3 connections to network) to organizations that address risk, liability, communication, and issue advocacy. Hence, those mitigating risks through regulatory authority and liability insurance and stakeholders that communicate to and advocate for the public are unlikely to have the opportunity to deliberate on the effects of urban nanotechnologies before they become real (up-stream or mid-stream engagement). The collective responsibilities focus, predominantly, on realizing market-oriented value with little regard to anticipating societal and socio-ecological risks, or the disruptive power of technology. There is evidence that while twenty-five of the responsibilities are present in the interviewees’ statements, eight normative responsibilities are absent from the collective understanding held by the stakeholder network. That finding along with the finding that not a single normative responsibility was universally expressed demonstrates a lack of attention is paid to risk, sustainability and anticipatory governance. A more nuanced finding is that there is a notable shift in the responsibilities from ‘upstream’ to ‘downstream’ phases and this indicates that the responsibilities of others ‘downstream’ are understood to a lesser extent. These characteristics stand in stark contrast to state-of-the-art governance in technology development (see Table 5).

Table 3.5

*Critical Constellations in the Agent Network of Nanotechnology Governance in Phoenix*
Evaluative criteria / Guidelines

Critical Constellations in Phoenix

Importance of connectivity (>2 connections to the network) between all stakeholders as a measure of collaboration, coordination, and shared learning.

Four key stakeholders are not sufficiently connected and embedded in the network (i.e. two or less connections to the network), specifically NGOs, insurers, media, and government regulatory agencies are isolated and only weakly connected to the core network.

Triple bottom line approach equally weights market-oriented, societally-oriented, and socio-ecological values as a measure of sustainability-oriented governance.

Economic values are highly dominant and overshadow societally-oriented and socio-ecological values.

Presence of all normative responsibilities as a measure of awareness for responsible innovation.

Eight responsibilities (A.1.ii, P4, C2, C3, C6, PC2, H3, H6) are left unaddressed.

Universal recognition of any of the normative responsibilities as a measure of commonly held, collective responsibility, within the stakeholder network.

Three normative responsibilities (A2, P2, S1) align with interviewees’ statements with the highest frequency, but not a single normative responsibility is universal among the stakeholder network.
Normative responsibilities are understood across all phases of innovation by the stakeholder network. There is a recognizable shift in responsibilities from early to late stages of innovation. The elicited responsibilities focus on ‘upstream’ innovation phases – initialization and experimentation; proof of concept. Fewer aligned with ‘downstream’ phases – commercialization and post-commercialization or holistic responsibilities. This is a measure of disconnect between stakeholders in an urban region and stakeholders with responsibilities in later phases of innovation.

**Lack of connectivity between key stakeholders**

The dominant groups identified by the actor network analysis (government funding and support & agencies, industry, and academic research institutions) typify the ‘triple helix’ of innovation (Leydesdorff & Etzkowitz, 1998). The results demonstrate that stakeholders who do not work towards commercialization, or could constrain innovation, are somewhat isolated from the core stakeholders in the network. This suggests a lack of connectivity between all key stakeholders. Furthermore, a lack of connectivity is an indicator that shared learning, a key component of sustainability-
oriented governance (Kemp et al., 2005), is not fostered within the stakeholder network. This finding supports the theory that the ‘triple helix’ of innovation is central and it reinforces earlier findings that a lack of connectivity impedes shared learning (Wiek et al., 2007)

*The single bottom line: Market value*

Market-based values dominate nanotechnology governance in Phoenix. This can be understood through two dominant economic theories (Solow, 1957; Solow, 1993). The first one identifies technological innovation as the critical exogenous force driving economic growth (Solow, 1957). This is supported with historical gains resulting from technological advancement, which perpetuate a cultural expectation that nanotechnology will do the same in the future. Solow (1993) also asserts that perfect substitutability between natural and manufactured capital can result in ‘weak’ sustainability. This reinforces the belief that technological solutions can displace ecosystem services without negative externalities arising. The substitutability between technological and natural capital are, however, imperfect and negative consequences abound as human replace ecosystem services with technological infrastructures. Organizations fostering ‘sustainable nanotechnology’ must confront this evidence and recognize that our findings do not align with the conceptualization of sustainability as a balance between economic, social, and ecological values (Hacking & Guthrie, 2008).

*A deficit of responsible innovation in Phoenix*

There are three key deficits in the governance of the innovation process. First, little attention is paid to the state-of-the-art normative responsibilities that can guide
responsible innovation of nanotechnology. The first is observed in the absence of eight normative responsibilities throughout the stakeholder network. A normative responsibility that is absent is A.1.ii, which states, “Consider equity explicitly … when awarding incentives.” This might be explained by the newness of this idea, published in 2011 by Cozzens. Yet other normative responsibilities are not new, including, P4, “Practice precaution...” and C2, “Ensure access to livelihood opportunities … by training a diverse community in the requisite skills” and C6, “Afford customers the choice to not purchase nano-containing products through labeling.” The precautionary principle, training diverse workforces and labeling products are widely discussed and debated. The lack of attention to these items seems to align with broader cultural and political values. The attention paid to these items is observed in numerous European chemical and materials management regulations (c.f. policies ranging from Registration, Evaluation, Authorisation and Restriction of Chemical substances to the Regulations on Hazardous Substances), to the well document response of Australians to a lack of clear labeling (Cummings, 2013), and South African nanotechnology working training programs (Cozzens, 2011). The United States political arena is not readily open to discussion of precautionary policies, labeling mandates (outside of the Food & Drug Administration), due in large part to coordinated lobbying and perceived harm that regulations have on the market. As for worker training, it is a shared responsibility that often lacks attention to diversity during the formulation of new educational degree and certificate programs. A rich body of academic literature from the risk governance, sustainability-oriented, and anticipatory governance are advocating for the importance of
these responsibilities, yet the evidence suggests a minimal impact on urban stakeholders.

Second, while three normative responsibilities are frequently expressed, the stakeholder network collectively holds none of the normative responsibilities. And while some may argue about the distribution of collective responsibilities versus the responsible individual, as discussed by Smiley (2010), there is a growing body of work that measures collective responsibilities (Whalan, 2012). It should be noted here that the three most frequently aligned normative responsibilities (A.2; P.2; S.1) all pertain to the responsibility of government funding and support agencies to shift the science policy agenda from commercial goals to issues of risk, societal implications, and sustainability. Government funding and support agencies might in turn respond by asserting that their mandates are an expression of the collective of voting citizens and their representatives in the executive and legislative branches of government. Surely, there is a collective responsibility for setting the science policy agenda that cannot be held, individually, by agencies funding and supporting science, technology and innovation (Owen, Stilgoe, et al., 2013). However, program directors at the federal level, directors of the Greater Phoenix Economic Council, who allocate resources to recruit and retain companies, and city economic development officers need to recognize the multiple benefits realized by promoting entrepreneurial efforts that not only create jobs, but synergistically promote a livable and sustainable community through the company’s culture, products and engagement in solving problems.

The third indication that there is a deficit of responsible innovation among the stakeholder network pertains to the distribution of normative responsibilities across the
innovation process – from ‘upstream’ to ‘downstream’ phases. The results depict a greater concentration of normative responsibilities that align with the ‘upstream’ phases of innovation. This may either signal a loss of control by stakeholders operating at the urban scale (or micro-level), as global commercial markets (i.e., the macro and meta-level) assume responsibility for market-based product distribution (Markard & Truffer, 2008). Our findings align with this theoretical construct, yet something else might be understood here. People have a hard time understanding the implications of their actions in far away places and, secondly, lack empathy for harms that do occur close to the places they live, work and play. If the science, technology and innovation activities that are most frequently occurring in the city are ‘upstream’ activities, then it makes sense that stakeholders’ statements on normative responsibilities align with ‘upstream’ responsibilities, rather than aligning with distant or future responsibilities.

6. Conclusion

The study yielded a normative framework of guidelines for responsible innovation. The framework provides stakeholders participating in nanotechnological innovation with normative guidelines for their actions ‘upstream’ and ‘downstream’ the innovation system.

The case study depicts a stakeholder network that is guided primarily by the belief that benefits are best distributed through commercial markets. Stakeholders did, however, express responsibilities that aligned with the normative responsibilities. With that in mind, stakeholders who are committed to nanotechnology innovation can realign with the goal of responsible innovation and start to address the gaps and weakness identified in
this study.

Certainly as more evidence is accumulated our current synthesis of the responsibilities will be augmented. Comparing the findings from this case study with other cultures, technologies, and across time, should yield interesting results. There is evidence of normative responsibilities that might be considered as ‘seeds of change’ to be cultivated and fostered as the governance regime transitions in the future. If the literature that contributed to this work is to be believed, then nurturing ‘seeds of change’ is essential for emerging technologies, such as nanotechnology, to contribute in positive ways to society as a whole.

This chapter contributes to the literature on the governance of emerging technologies by overcoming disciplinary barriers and synthesizing literature from risk governance, sustainability-oriented governance and anticipatory governance. This study links normative responsibilities to actors and phases of innovation and thus contributes to sustainable anticipatory governance as a means to design, in a proactive manner, a governance regime. The empirical research presented demonstrates the value of the framework as an evaluative tool, which can identify strengths, weaknesses, and gaps in a given governance network.
Chapter 4

Scenarios of Nanotechnology Innovation Vis-à-vis Urban Sustainability Challenges

1. Introduction

Nanotechnology is considered an important means for addressing urban sustainability challenges ranging from climate change and water contamination to access to healthy food and public safety (Smith & Granqvist 2011; Wiek et al., 2013). While the potential is immense, the innovation and governance structures eventually determine what nanotechnologies are actually being developed and implemented. Yet, current structures and processes for innovating and governing nanotechnology display various deficits (Foley et al., in prep; Maclurcan & Radywyl, 2012). There is an overemphasis on generating economic benefits without considering adverse societal and environmental impacts (Karn & Bergeson, 2009). Public engagement and civic dialogue are both means to address future uncertainty and consider broader value sets. Yet, key stakeholders at the core of nanotechnology innovation are apprehensive about public engagement (Rip & Shelley-Egan, 2010). Compounding the situation further, entire suites of nanotechnologies are being innovated, today, with few venues for broader civic dialogue and engagement (Grieger, Wickson, et al., 2012). At the same time, nanotechnology innovation is insufficiently responding to sustainability challenges with ‘end-of-the-pipe’ and ‘high-end’ solutions that are incapable of addressing root causes (Cozzens & Wetmore, 2011; Wiek et al., 2012).

A variety of different stakeholder groups, including governmental agencies,
socially-oriented entrepreneurs, environmental and citizen advocacy organization, as well as sustainability scholars, alike, are converging in their assessment that there is a pressing need for alternative models of nanotechnology innovation and governance (Renn & Roco, 2006). In particular, responsible innovation, sustainability, and anticipatory governance have emerged as powerful guiding concepts that resonate with diverse positions and perspectives (Wiek et al., 2007; Guston, 2008; Roco et al., 2011; Von Schomberg, 2013).

Citizens, city officials, entrepreneurs, corporations, however, are overwhelmed with the maelstrom of day-to-day operations, with little capacity left to explore long-term futures. Scenarios offer opportunities to explore future nanotechnology applications and appraise potential impacts (positive and negative) (Renn & Roco, 2006; Robinson, 2009; Wiek et al., 2009). While researchers in academia and industry have created an abundance of scenarios of future nanotechnologies, there is, however, a paucity of scenarios that explore alternative models for innovating and governing nanotechnologies.

The study presented here offers such an exploration, addressing two questions: What could be the future implications if the current dominant innovation and governance models continue, or, in contrast, if alternative ones would emerge? And how conducive to responsible innovation and anticipatory governance are these different models? In order to make this exploration tangible and linked to real innovation and governance practices, we focus here on nanotechnologies for urban buildings, spaces, and infrastructures, including multifunctional surface coatings, energy production, transmission and storage systems, genetically-based security applications, enhance
structural capacity from nano-polymers to reinforced concrete, as a few examples. Our research objective is to create a unique set of diverse scenarios that consider the future implications of nanotechnology innovation in an urban context, in particular its response to urban sustainability challenges (Wiek et al., 2013).

There is a crowded landscape of nanotechnology scenarios, primarily derived from expert-guided prognostications. This study shifts away from a techno-centric perspective that begins with nanotechnology as an objective that arrives and spontaneously creates vast impacts. Rather, this study positions the very governance and innovation processes shaping nanotechnology at the nexus of the study to explore the research question. In practice, this repositioning allows contemporary decision-makers to understand their own responsibilities in shaping and contributing to governance and innovation processes, respectively.

2. Research Design and Methods

2.1. Conceptual framework. The research design draws upon four linked design elements, namely, urban sustainability challenges, innovation model, nanotechnology applications, and societal context (see Figure 4.1). The conceptual framework centers on the mode of technological innovation (or governance). We explore if and how society responds (or not) to challenges by ways of innovation (innovation model). The innovation process results in nanotechnology applications, which do or do not address urban sustainability challenges. The societal context comprises enabling and constraining factors that influence the innovation process. The four elements feed back and mutually reinforce each other.
The *innovation model* is constituted through different stages and corresponding activities carried out by various stakeholders. The innovation activities depend on the learned behaviors that guide actors (people with roles in the system) as they shape the process outcomes (Gorman, 1999). Process outcomes, created in each phase of innovation, take the form of proposals, papers, patents, prototypes, pilot projects, and products, as a few examples. *Nanotechnology applications* interact in particular ways with urban life, including, but not limited to, multifunctional surface coatings, energy production, transmission and storage systems, genetically-based security applications, enhance structural capacity from nano-polymers to reinforced concrete. *Urban sustainability problems* are complex constellations of causes and effects that display severe long-term adverse impacts on economy, environment, and society (Wiek et al., 2012). The *societal context* is a dynamic set of capacities that both enable and constrain the innovation process, and also indicate how a society responds to challenges. The societal context includes, politics, values, societal roles and hierarchies, resources, regulating conditions, and social networks.

*Figure 4.1. Conceptual framework linking innovation model, nanotechnology*
applications, urban sustainability challenges, and societal context.

2.2. Quality criteria. It is imperative that scenario studies adhere to quality criteria that offer boundaries across the spectrum of what is possible to likely. Scenario studies that lack quality criteria may as well be exercises in wishing for rainbows or brooding over rain clouds. This study employs four quality criteria – systemic, coherence, plausibility and tangibility (Wiek & Iwaniec, in press) – to support the legitimacy of the scenarios. Each quality criteria is articulated and justified below.

2.2.1. Systemic criterion. Systemic criteria can be defined as how scenario elements are interlinked between drivers and impacts with dynamic feedback loops (Wiek & Iwaniec, in press). This criterion can be evaluated in a binary way. Either the scenarios demonstrate linkages and feedbacks or they do not. To meet this criterion, design elements must have cause-effect relationships through direct and indirect connections. Scenario-specific system maps ensure adherence with this criterion and reflect Smits et al. sentiments on innovation as, “a systemic process involving a heterogeneous set of actors” (2012, pp. 387).

2.2.2. Coherence criterion. Coherence can be defined as scenarios that are consistent and contain neither inconsistencies nor conflicting logic. The total number of inconsistencies is used to evaluate coherence. Scenarios with less than ten inconsistent variable interactions are considered relatively coherent (Wiek et al., 2009). To meet this criterion, the analytical and intuitive scenario methodologies both rely upon a consistency matrix, which is described in Section 2.3 and is reported in the results section.

2.2.3. Plausibility criterion. Plausibility can be defined as “holding enough
evidence to be considered ‘occurrable’ – to become real, to happen” (Wiek, Keeler, et al., under review). A scenario is considered plausible if the scenario elements (a) have been implemented in the past, or (b) elsewhere in the world, or (c) have been demonstrated realizable (proof of concept), often through pilot projects” (Wiek and Iwaniec, in press, pp.7). This study adheres to the plausibility criterion by relying on variables and projections that are supported by an evidence-base of scientific, media and government sources.

2.2.4 Tangibility criterion. Tangibility is a way to make future scenarios accessible at a scale that is appropriate to the targeted decision-maker (Shaw et al., 2009). Tangibility is often through created through 2-D and 3-D graphics that evoke emotion and leverage important places in a community. Alternatively, narratives can be used to tell the story in an understandable and visceral manner. In this study scenario narratives are employed to adhere to the tangibility criterion. The narratives tell stories about how people live, work, and recreate in the nano-enhanced city from a personal perspective.

The four components of the conceptual framework are operationalized through a set of variables and future projections (see Table 4.1). Variables and future projections were selected based on literature review and interviews. Our review captured a diverse array of data sources that are flexible enough to inform both the analytical and intuitive scenarios and draw upon top-down (i.e. expert contributions and literature) and bottom-up (i.e. practitioner interviews and locally published reports and media) inputs. Aiming at plausible scenarios, we identified and defined future projections that were supported by scientific, media, and government sources (Wiek, Keeler, et al., under review).
<table>
<thead>
<tr>
<th>Societal Context</th>
<th>Variables</th>
<th>Future Projections</th>
<th>Sources</th>
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<tr>
<td></td>
<td>Capacity</td>
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<td></td>
<td>Capacity</td>
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<tr>
<td></td>
<td>Academic Capacities</td>
<td>1. Decreased capacity 2. Status quo (i.e. inflationary growth) 3. Marked increase</td>
<td>Rosenberg and Nelson 1994; Feldman et al. 2002; Sampat 2005; Crow 2010</td>
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<td></td>
<td>Risk Mitigating Capacity</td>
<td>1. No clear roles (anything goes – ad hoc) 2. Reactive policies 3. Anticipatory &amp; Precautionary</td>
<td>Renn &amp; Roco 2006; Brown 2009; Philbrick 2010; Grieger, Baun et al. 2010; Bosso et al. 2011</td>
</tr>
<tr>
<td>Social, Legal, Ethical, and Civic Capacity</td>
<td>1. Low (not considered) 2. Acknowledged and enlightenment approach is take to address issues 3. High awareness and mitigation attempted</td>
<td>Guston 2008; Wiek et al. 2008; Delgado et al. 2011</td>
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<tr>
<td>Innovation / Governance Model</td>
<td>1. Linear Model (Dominant); 2. Market Pull (Dominant); 3. Closed Collaboration (Dominant); 4. Social Entrepreneurship (Dominant); 5. Open Source &amp; Do-it-yourself (Dominant)</td>
<td>von Hippel 1988; Balogh 1991; Porter 1990; Kuhlmann &amp; Edler 2003; Sampat 2005; Mulgan et al. 2005; Boettiger &amp; Wright 2006; Alic 2007; Almirall and Casadesus-Masanell 2010; Berglund et al. 2012; Pennink 2012</td>
<td></td>
</tr>
<tr>
<td>Nanotechnology in Transportation System</td>
<td>1. High cost good distributed via market 2. Low cost good distributed via market 3. Accessible as public good</td>
<td><a href="http://nice.asu.edu">http://nice.asu.edu</a></td>
<td></td>
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<tr>
<td>Nanotechnology in Water Systems</td>
<td>1. High cost good distributed via market 2. Low cost good distributed via market 3. Accessible as public good</td>
<td><a href="http://nice.asu.edu">http://nice.asu.edu</a></td>
<td></td>
</tr>
<tr>
<td>Nanotechnology in Medicine and Nutrition</td>
<td>1. High cost good distributed via market 2. Low cost good distributed via market 3. Accessible as public good</td>
<td><a href="http://nice.asu.edu">http://nice.asu.edu</a></td>
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<tr>
<td>Nanotechnology in Security and Defense</td>
<td>1. High cost good distributed via market 2. Low cost good distributed via market 3. Accessible as public good</td>
<td><a href="http://nice.asu.edu">http://nice.asu.edu</a></td>
<td></td>
</tr>
<tr>
<td>Nanotechnology in Energy Systems</td>
<td>1. High cost good distributed via market 2. Low cost good distributed via market 3. Accessible as public good</td>
<td><a href="http://nice.asu.edu">http://nice.asu.edu</a></td>
<td></td>
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<tr>
<td>Nanotechnology in Construction &amp; Built Environment</td>
<td>1. High cost good distributed via market 2. Low cost good distributed via market 3. Accessible as public good</td>
<td><a href="http://nice.asu.edu">http://nice.asu.edu</a></td>
<td></td>
</tr>
<tr>
<td>Urban Sustainability</td>
<td>1. Status quo reliance on housing and consumerism 2. Housing and consumerism creates a decreased share of the state revenues.</td>
<td>ADA 2011; BLS 2011; Henig 2010; MCOMB 2009; Gober &amp; Trapido-Lurie 2006</td>
<td></td>
</tr>
<tr>
<td>Topic</td>
<td>Challenges</td>
<td>References</td>
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<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>Electrical Energy Challenges</td>
<td>1. Fossil fuel based energy sources are dominant 3. Renewable energy sources are dominant</td>
<td>ACCAG 2006; Mahrer 2011; Grimm et al. 2008; Dalrymple &amp; Bryck 2011</td>
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<tr>
<td>Water System Challenges</td>
<td>1. Water sources are depleted faster than recharged 2. Water use is in balance with socio-ecological system</td>
<td>Wiek &amp; Larsen 2012; Gammage 2011</td>
<td></td>
</tr>
<tr>
<td>Urban Mobility Challenges</td>
<td>1. Automobiles are dominant 2. Multi-modal transit systems are dominant</td>
<td>MAG 2011; FHWA 2011; Wender et al. 2012; Machler &amp; Golub 2012; Ross 2011</td>
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<tr>
<td>Health &amp; Nutrition (e.g. childhood obesity)</td>
<td>1. Chronic health diseases are highly impactful 2. Chronic health diseases are rare</td>
<td>Crouch 2011; Talbot 2012; Cutts et al 2009; Lathey et al., 2009; CDC 2010</td>
<td></td>
</tr>
<tr>
<td>Education and Life Long Learning Challenges</td>
<td>1. Public education is incapable of producing students with adaptive learning skills and those that can remove children from public schools 2. Public education produces students capable of adaptive learning, regardless socio-economic status</td>
<td>MIPP 2010; Hart &amp; Hager 2012</td>
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</table>
2.3. **Case study: Metropolitan Phoenix.** Cities are the world’s centers of human activity and of technology innovation activities, including patenting and publication, as well as commercialization activities. This applies to nanotechnology innovation, in particular (Youtie & Shapira, 2011). To make the study tangible and accessible to a multitude of stakeholders with whom we have been engaging in place-based and socially-embedded research for several years, the urban location of Phoenix was selected as the focus of the scenario study. Phoenix, attempting to overcome the recent distinction of being named the world’s least sustainable city (Ross, 2011), offers a host of sustainability challenges, which are complex and intertwined. The research team’s commitment to working with city officials, nanotechnology organizations, and citizens toward a sustainable future, creates an atmosphere for participatory scenario construction to be viable (Wiek et al., 2009). The scenario study builds upon previous studies on current innovation practices in Phoenix (Foley & Wiek, in prep), as well as the alignment (or non-alignment) of the current innovation and governance regime with principles of risk governance, sustainability, and anticipatory governance (Foley et al., in prep).

2.4. **Methodology.** The study uses a mixed methods approach, linking intuitive and analytical scenario construction (Wiek et al., 2006). Intuitive scenarios based on creative thinking aim to explore futures through compelling stories; however, they often lack the coherent and systemic focus of analytical scenarios. Conversely, analytical scenarios often fail to resonate with and inspire stakeholders, leaving the message unheard. The combined methods approach applied here allows for inspiration while ensuring analytical rigor. Those two methodologies were carried out simultaneously, each
feeding back to and refining the other. A comparative analysis enabled a final synthesis (see Figure 4.2). The mixed method design can be classified using (van Notten, Rotmans, et al., 2003) schemata as having normative project goals that use forecasting as a means for exploration. The process design marries intuitive and formal methods. The scenario context embodies the characteristics of a complex scenario – i.e. heterogeneous, peripheral, alternative, and highly integrative (or systemic).

**Figure 4.2.** Hybrid approach linking analytical and intuitive scenario construction.

The analytical scenario construction is based on Scholz & Tietje (2002) and Wiek et al. (2009). First, a consistency analysis (Tietje, 2005) was performed, using the variables and future projections detailed in Table 1. Evidence from literature supported the assignment of consistency values. Inter-rater reliability testing was conducted in a workshop and interviews with expert stakeholders. Ten percent of the ca. 1,300 cells of
the consistency matrix were identified (5% randomly and 5% targeted selections) for inter-rater reliability testing and discrepancies were reconciled. Second, an initial set of scenarios was selected, using Systaim® with filters set to no inconsistency and a minimum additive consistency value of at least 75 to ensure that only highly consistent scenarios resulted (11,486). Third, a hierarchical cluster analysis of the initial set of scenarios as conducted. Chi squared analysis between variables was employed to generate four clusters. The fourth step was a diversity analysis of the clustered scenarios (Wiek et al., 2009). The diversity analysis validated that the clusters were sufficiently diverse (diversity threshold set at 20%) (Tab. 2). This indicates that the analytical scenarios could be clustered in four diverse groups prior to the comparison with the intuitive scenarios.

Table 4.2

*Diversity Analysis*

<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>270447</th>
<th>226747512</th>
<th>113863749</th>
<th>225500382</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Cluster No.)</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>270447</td>
<td>90% (18)</td>
<td>25% (5)</td>
<td>50% (10)</td>
<td></td>
</tr>
<tr>
<td>226747512</td>
<td>75% (15)</td>
<td></td>
<td>20% (4)</td>
<td></td>
</tr>
<tr>
<td>113863749</td>
<td></td>
<td>40% (8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>225500382</td>
<td></td>
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</table>

*Note.* The diversity values expressed a percentages and the unique divergences (in brackets) result from comparing two scenarios along the 20 impact variables (100% = all differ; 0% = all match) for scenarios selected from the four clusters. The results
were used in the comparative analysis for selecting the final set of scenarios (see below).

Intuitive scenarios were built in as an iteration of previous studies (Foley & Wiek, in prep; Foley et al., in prep). To gain additional insights into the future of nanotechnology innovation an array of sources were gathered, including: interviews, workshops, public events, public engagement exercises, media, and literature review. Scenario narratives, day-in-the-life stories, were constructed using narrative non-fiction writing techniques (Gutkind, 2012). Each narrative used a different innovation model to guide the story and to describe the culture of innovation (societal context) in the scenario. The narratives made a point of describing emblematic nanotechnology applications in-use or under development, while also directly commenting on the status of various urban sustainability challenges. First drafts of the scenarios relied upon many of the factors/elements described in Bennett (2008) and Wiek et al. (2013). Each scenario begins at sunrise and this serves to ground the reader. The setting for each scenario is in the urban environment. Characters are fictional, but character development relied upon the authors’ experiences. The initial narratives were deconstructed using the variables and future projections (Tab. 1). Projections were inserted using brackets directly into the narrative’s text. For each scenario, a scenario-specific table of all variables and projections was constructed. These tables were then used to create scenario-specific consistency matrix in order to reveal inconsistencies and synergies within the scenarios. Two of the selected scenarios (A and B) had no inconsistencies, while the other two (C and D) had six and three inconsistencies, respectively. Based on this analysis, narratives were amended, keywords changed, and elements added to enhance the internal
consistent of the scenarios.

The comparative analysis started with selecting scenarios based on the results from the analytical scenario construction (above). Scenarios that were highly similar to the intuitive scenarios were identified and selected. The paired scenarios (analytical and intuitive) were aligned using their respective sets of projections. The two sets of projections were analyzed using scores from 1 for complete disagreement, to 0 for complete agreement. The comparative analysis resulted in one intuitive scenario with low agreement (0.35), one with moderate agreement (0.20) and two with high agreement (0.05 and 0.15 respectfully) (Tab. 3). The two intuitive scenario with the lowest agreement (C and D) can be explained by the scenario specific consistency analysis. Both of those intuitive scenarios have >1 contradictory interaction and therefore could not be entirely aligned with the filtered set of highly consistent analytical scenarios. The level of agreement, however, is most surely enhanced with the use of the scenario-specific consistency matrix and the refinements that reduced known inconsistencies.
### Table 4.3

**Scenario Agreement**

<table>
<thead>
<tr>
<th>Intuitive Scenarios</th>
<th>Analytical Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Will the sun rise in Arizona?</td>
<td>Sc: 270447 (1) 85% (3)</td>
</tr>
<tr>
<td>B: Citizens &amp; cities</td>
<td>Sc: 226747512 95% (1)</td>
</tr>
<tr>
<td>C: Controlled &amp; securitized</td>
<td>Sc: 113863749 65% (7)</td>
</tr>
<tr>
<td>D: Grey goo revisited</td>
<td>Sc: 196632988 80% (4)</td>
</tr>
<tr>
<td></td>
<td>Sc: 225500382 (4)</td>
</tr>
</tbody>
</table>

Note. The table shows the agreement of two scenarios along the 20 impact variables (100% = all match; 0% = all differ) for the intuitive and selected analytical scenarios, listed by scenario number (Sc:) with cluster numbers in brackets. Total divergences are brackets following the percentage of agreement.

Following Wiek et al. (2009), a qualitative system analysis identified
variable are currently active, mediating, passive and background drivers. This was supported with the earlier research (Foley & Wiek, in prep). For each scenario the future-projection of each variable was inserted into a scenario-specific system map. The analytical interpretation of the scenario-specific system maps rigorously depended upon the qualitative system analysis.

3. Results

3.1. Scenario narratives, descriptions, and system maps. Four distinct scenarios draw upon the five different nanotechnology innovation models discussed in Foley & Wiek (in prep), and offer an opportunity to explore the future nano-enhanced city. The scenario narratives offer a glimpse into a scenario from a day-in-the-life experience – see Addendum A for the scenario narratives. Scenario descriptions analyze key points from the ‘glimpse’ and start with the scenario’s thesis. The descriptions detail enabling and constraining factors guiding actors’ decisions. Questions of access to and distribution of nanotechnology (i.e. via the market or via non-market mechanisms) are addressed, along with the benefits realized and negative impacts. This gets at the outcomes of nanotechnology in the city and the amelioration (or persistence) of urban sustainability problem. Scenario-specific system maps are linked directly to the descriptions and call out the interlinked nature of the variables (active, mediating, passive and background drivers) within each scenario.

3.1.1. Will the sun rise? How markets pull innovation. Societal responses to urban sustainability challenges have not progressed and adapted to the increasing pressures that result from the lack of social cohesion and justice, livelihood opportunities,
as well as resource depletion and large-scale urban contamination. Government, business, academia, and civic society continue business- and politics-as-usual. Socio-economic segregation paired with individual consumerism is the norm. These practices undermine the collective pursuit of public interests and the protection of public goods. The lack of sufficient responses to the urban sustainability challenges has led to the aggravation and amplification of stresses on people, economy, and environment. Society is deeply divided along people’s socio-economic status and means.

The dominant innovation model in this scenario is commonly called ‘market pull’ (active variable). The market-based mechanisms fail to create disruptive, societal-oriented, innovation. Consumers demand low cost products (mediating variable) that are provided by private corporations and entrepreneurs, alike. Consumer preference drives nanotechnology innovation in convenience-based products. Existing large infrastructures gain enough efficiency to out compete rival technologies, such as technologies that may disrupt the existing system (passive variable). The ‘free’ market perpetuates carbon dioxide pollution and social injustices (background variable).

In this scenario, nanotechnology applications support path dependency and optimize fossil fuel based energy resources, including natural gas, petroleum, coal and nuclear energy resources. Efficacy in battery technologies has shifted transportation from internal combustion to electrical motors, yet the energy sources remains linked to existing electrical power supply technologies. Nanotechnology applications in construction materials create novel means of moving people through buildings, however, these novel technologies are present in only a small number of buildings, primarily those constructed
recently.

Communications systems generate greater volumes of data, yet this vast flood of information is channeled by consumers’ preference. There continues to be a growing divide between people based on media preferences and this divide is re-enforced by marketing and advertisement campaigns (background variable). Society responds reactively to the latest disasters, via liability suits and product recalls (see mediating variable) Public funding and support for nanotechnology is unresponsive to societal challenges and is aligned primarily with market-based product commercialization (see active variables)

Existing urban sustainability challenges are perpetuated (background variable). High-wealth persons can afford basic amenities, as well as, the luxury goods offered by the markets. Corporations realize various degrees of success and failure with net profits equaling the cost of production plus marketing and overhead minus net revenue. Externalities are not included in profitability statements. Fossil fuel based emissions and urban sprawl continue to grow as the urban boundary expands with highway construction and consumerism drives the economy. Water resources are depleted faster than recharge rates. Citizens are divided by socio-economic conditions and purchasing power, and this is seen as normal. Wealthy families remove their children from poor performing public schools in favor of private education. Chronic behavioral diseases, created by consumer preferences for processed foods, are managed pharmacologically. Poor urban air quality and increased nighttime temperatures intensify in Phoenix.
Figure 4.3. Scenario specific system map: Scenario A.

3.1.2. Citizens and cities: collaboration via social entrepreneurship. Society has developed a unique practice of collectively addressing urban sustainability problems. Responses rely on intensive and continuous collaboration across multiple scales and different sectors of society; civic literacy and engagement is very high. This has led to transformative solutions that have alleviated stresses on people, economy, and the environment and reduced future risks. Society is united in its pursuit to create healthy, vibrant, just, and diverse communities across the city.

Social entrepreneurship (active variable) brings civic society (the public, broadly) together to work in collaboration with government agencies (city, state, federal and international) to identify problems that demand technological innovation and behavioral change (societal innovation). The ‘user’ (society civic) is positioned in a privileged position with the government highly attuned to societal needs (see active variables). Solving societal challenges is the originating force of innovation (active variable) and sets the science policy agenda, including funding priorities and awards. Civic society
takes responsibility for identifying sustainability challenges and for contributing to comprehensive strategies to address root causes through behavioral change and technological innovation (background variable). Within this model, there are a few key constraining factors including initial and sustained commitment from citizens and civic leaders to long-term problem-solving process, evaluation of potential solutions, implementation and program maintenance. Cultural expectations around immediacy and simple solutions fade as the efficacy and societal benefits are experienced across the entire Phoenix metro area.

An enabling factor for long-term investments and societal-oriented entrepreneurial capacity is the application of hyperbolic discounting rates in 2050 by public lenders. The historical concept of positive discounting rates is abandoned as the value of historical buildings and longer-term infrastructure planning to gain auxiliary capital overtime. Hyperbolic discounting rates and net zero discounting rates are being called for today to enable inter-generational equity and address longer-term urban sustainability projects (Heal, 2000).

Risks are mitigated through anticipatory and precautionary tactics that are applied through clear roles, which are transparent to everyone (mediating variable). This brings together people from all walks of life together to address urban sustainability challenges. For example, city officials amend building codes to address the urban heat island effect. Zoning demands responsive paneling, which uses nano-enabled materials, to be installed as part of the building envelop in all new commercial structures or otherwise prove that new buildings will decrease localized urban heat island impacts. Nanotechnology is
created through public-private partnerships to address various issues (*passive* variables). Responsive panels are developed to reflect solar heat, while generating electricity; nighttime temperatures are cool and refreshing in Phoenix. Massive financial and land use commitments to public transit realize benefits from ‘smart grid’ and ultra-lightweight vehicle construction. The complete street model, once constrained to the dense streets of Europe has overtaken the wide boulevards of Phoenix, with pedestrians, carbon fiber bicycles, ultra-lightweight electric cars, trains and buses moving through segmented streets, which are shaded with native vegetation and overhanging building facades. Air and water quality are maintained with nano-porous filters and monitored with nano-enabled sensors placed throughout the city. Personal and commercial use of public goods (including air and water) is reported, in real-time, via radio frequency enabled communications systems, to the appropriate city department. The data is published in weekly reports, reviewed and approved by village councils. Consumers purchase goods and services through the market, but tax revenues and consumer spending account for a decreased share of the state’s economy. Non-commercial mechanisms (i.e. public infrastructures) allow for beneficial nanotechnology applications to be largely accessible to all (*mediating* variables).

Citizens, city leaders, and corporate partners are slowly addressing historical groundwater issues, historical overinvestment in highways, and underinvestment in public education with a concerted effort. The challenges of collaboration, retaining stakeholder buy-in and maintaining the city infrastructure are not trivial. Yet, the widespread urban sustainability challenges noted by historians in the 1990s and into the 2020s
have largely vanished due to concerted efforts to change behaviors and introduce technologies that intervened in positive, lasting, ways (background variables).

3.1.3. Controlled and securitized: Closing in on freedom. Society has responded to urban sustainability problems (internally and externally created) by concentrating power in large administrative units that assert control over all aspects of society, technology, and infrastructure. This has led to the containment of threats and has mitigated some of the stresses on people, economy, and environment. Yet, society pays the price for its security through the loss of perceived and real freedoms and civic accomplishments.

Closed collaboration (active variable) is the dominant innovation model and aligns mission-oriented government agencies (e.g. Department of Defense, National Institutes of Health) and private contractors to create technological and behavioral

Figure 4.4. Scenario specific system map: Scenario B.
solutions. Public funding and support for nanotechnology is closed to all, but a very few highly privileged decision-makers, with the intent of preserving secrecy, excellence, and adherence to the core mission (active variable). Future success is predicated on historical successes – e.g. atomic bomb and penicillin. The innovation model reacts to societal problems (mediating variable), yet the limited number of perspectives constrains the project teams at times. Another constraint includes budgetary limits (imposed at some point), knowledge deficits and the inability to foresee unintended consequences. Urban sustainability challenges are addressed with controlled deployment of nanotechnology (active variables).

Universal healthcare, via personalized medicine, is provided through real-time vitals, genetics and blood-based diagnostics coupled with analytics and pharmacological treatments. Security systems are integrated into the building appliances, infrastructures and communicate to a regional authority (passive variable). All the while limited supplies of water and energy are allocated and delivered to residents. Core societal values for water, energy, personalized medicine and security create the onus for government agencies to partner with private corporations and provide those services to all citizens through non-market mechanisms (mediating variables). Local water restrictions create limitations to the city’s growth and the regional energy system relies almost exclusively on solar and geothermal sources.

The public goods delivered garner unquestioned public support and funding. Citizens are rarely, if ever, considered or engaged in decision-making (background variable). The city is reminiscent of Singapore; all clean and shiny with high levels of
social tension under the surface. Lower income socio-economic groups are clearly segregated. A plethora of urban sustainability challenges persist, despite the significant achievements toward a stable (energy, water, and state security) and healthy (personalized medicine) society in Phoenix. The universal security system does little to alleviate social tensions, including the familial connections between Phoenix residents and foreign nationals (i.e. illegal immigrants). Personalized medicine does little to prevent chronic behavioral diseases and instead resources are expended treating obesity with pharmaceuticals. Housing and consumerism and automobiles continue to drive the regional economy and perpetuate the divide between the ‘haves’ and ‘have nots.’ Water scarcity forces centralized water systems to impinge upon upstream and downstream stakeholders. Historical precedence continues to redistribute water resources in an inequitable manner, based on land area owned. The children raised in Phoenix and educated in public schools are subjected to a memorization-style education system that is not capable of producing students with adaptive learning skills and those that can are removing their children from public schools (background variable).
Figure 4.5. Scenario specific system map: Scenario C.

3.1.4. Grey goo revisited: how open source goes mainstream. Society has responded to urban sustainability problems by allowing people with the ability to manipulate the system to affect the quality of their own life and their community (if they are inclined to do so). There is no systematic public coordination; hackers are free to address any kind of problem in ad-hoc and random ways in specified locations. Whoever has an idea and the chance to manipulate the urban environment does so through distributed networks. This leads to scattered success in some places, as well as failures in other places, in which communities continue to experience stresses on people, economy, and environment.

Open source and do-it-yourself (DIY) innovation are the dominant models (active variable). Competition, skill levels, and alternative ways of thinking are the criteria for including (or excluding) people. Open source innovation is not without societal hierarchies or inequities. Those who can perform specialized tasks, contribute to
problem-solving activities and work within larger teams are most successful, yet the do-it-yourself element hints at the continued importance of individuals to make their own goods and services. Government agencies occasionally provide venues that address urban sustainability challenges in random and scattered ways (*active variable*).

Individuals are given the opportunity to solve problems in any way that they chose (*mediating variable*).

The education system creates talented, adaptive learners, skilled in problem solving and highly competitive, yet able to work in collaborative settings toward common goals (*active variable*). Those persons that do not succeed educationally are seen as constraining the open source innovation ethos and are deemed second-class citizens and are left to perform menial service-industry style tasks. Open source is a newer way to think about innovation and there are issues of trust and acceptance within traditional bureaucratic agencies that seek order, rather the organized chaos observed. The open source ethos and the belief that skills and hard work are the societal differentiators align with historical values of individualism, freedom and liberty held by Phoenicians. Citizens are bombarded with messages about the value of open source innovation and the accomplishments of ‘crowd sourcing’ (*background variable*).

The city is rife with nanotechnologies, atoms are the building blocks used by individuals (*passive variables*). The building blocks for almost any nanotechnology are readily available and 3-D (three dimensional) printers combine atoms to specified tolerances at a moments notice. This tool, available within an open source innovation community, allows for most products (bicycles, cars, small airplanes, solar panels) to be
built from scratch, if you have the time and understanding to make it. Nanotechnology applications are low cost goods, based on the price of specific atoms, (mediating variable). Some materials are unique to the maker, while others are larger architectural materials are shaped like clay to form exterior and interior walls. There are no rules against building materials or restrictive building codes. Hydrophilic and hydrophobic surfaces extract water molecules from seemingly dry desert air and soil moisture levels activate water systems. The urban fabric is divided between the random location of hacker ‘pads’ and the orderly residences owned by the ‘squares’ that follow the historical grid of one-mile by one-mile roads that run along the exterior of truly ancient agricultural fields.

Many urban sustainability challenges have been addressed through the collective actions of a highly educated population. The computing power available to citizens and to large global organizations allows for the creation of entirely virtual worlds that are an alternative reality for problem solving and a testing ground for theoretical solutions. That alone started to address social inequities and bring disparate communities together. Children, empowered and motivated, started to learn how to care for themselves, to eat nutritious foods, to exercise, to analyze problems, to be creative and adaptive in their learning. Another urban sustainability challenge, the urban heat island effect, experienced for decades, has been alleviated with high-density shading and responsive building facades that reflect heat and provide evaporative cooling. The electrical energy grid, once thought of as resistant to solar power’s variable loading rates, is now entirely sourced by local solar and geothermal sources.
None-the-less, there are imbalances and legacy issues that have not been addressed. Water resources continue to be exploited and a sustainable yield, balancing water use and natural recharge rates, is still an unrealized goal. Additionally, the urban form continues to expand, as does the reliance on personal automobiles. The land use, ecological, and societal impacts continue to grow with the expansion of the urban fringe (*background* variable).

**Figure 4.6.** Scenario specific system map: Scenario D.

## 4. Discussion

This participatory scenario study suggests that the current two dominant models of nanotechnology innovation and governance (market-oriented, and closed-collaboration military model) might amplify the current lack of social cohesion, livelihood opportunities, as well as resource depletion and large-scale contamination. Society might get further divided along people’s socio-economic status and means. Social tensions and outburst of violence might get mitigated with even greater dominance, surveillance, and
other control mechanisms (employing suitable nanotechnologies).

Alternatively, governance models with high levels of public participation or open-source activities that could create a new ‘triple helix’ of innovation, linking public agencies, risk mitigating actors, and civic society. Society might develop a unique practice of collectively addressing urban sustainability problems. This could lead to transformative solutions, including particular types of nanotechnologies that alleviate stresses on people, economy, and environment. Four distinct scenarios were constructed and offer an opportunity to explore the future nano-enhanced city. The future projections of three key societal capacities (risk mitigating capacity; social, ethical, legal, and civic capacity; and public funding and support capacity) support alternative innovation models. This results in alternative values embedded in nanotechnology applications. Innovation process assigns value to the use the creation and deployment of nanotechnology, they either address (or perpetuate) urban sustainability challenges.

The scenarios speak to science, technology and innovation policymakers and can assist those committed to short-term roadmaps (Yasunaga et al. 2009) to understand the diversity of value and influencing mechanisms explored in these longer-term scenarios. Avnimelech and Feldman (2010) present evidence on the rate of start-up companies that spawn from larger firms – creating the onus to recruit large companies, yet these scenarios force urban economic development officers to reflect on their role in shaping technologies and subsequently, reshaping their cities. The scenarios address both the socio- as well as the technical dimensions of socio-technical change as depicted by Geels (2002). The scenarios build upon the notion that Phoenix, an urban innovation cluster, is
operating at a niche-level and is pushing and being pushed by landscape and regime level changes, as depicted by Geels & Schot (2007). Furthermore, the scenarios illustrate the complex adaptive system that is innovation and reflect the interplays and tensions expressed by Kemp & Rotmans (2009).

There is little room for responsible innovation and anticipatory governance in a market-oriented innovation model that is simply profit seeking and holds a rigid belief that the market will distribute benefits equitably. Likewise, closed collaboration among an elite decision-making group of individuals bent on national security at all cost, regardless of impingements on freedom and privacy. Closed collaboration is responsible for national security, not equitable and just outcomes. Social entrepreneurship demonstrates a strong affinity for high public engagement, precautionary and anticipatory risk governance and high levels of government support for civic society. This model appears to be the most promising for responsible innovation and anticipatory governance to flourish. And finally, open source innovation, while a newer phenomenon may address certain urban sustainability challenges creatively and collectively, yet may also result in unstructured and random acts of nanotechnology innovation. Outcomes could be vastly different and a lack of clear risk governance is worrisome, to say the least. However, this mode of problem solving cannot be disregarded off-hand. There are promising elements and opportunities in the open source innovation model to explore further.

5. Conclusion

There are clear and articulated differences across the four scenarios that reflect
alternative outcomes for the city. The scenarios offer four alternative innovation models with four distinct future outcomes that couple the science and engineering at the nanoscale with diverse sets of societal values. The different alignments of governance among all actors, but most importantly among public agencies, risk mitigating actors, and civic society inform the innovation processes and in turn will have future impacts on the role and effects of nanotechnology in cities.

Three key societal variables (public funding and support capacity; risk mitigating capacity and social, ethical, legal and civic capacity) are critical to the urban sustainability challenges. This study in intended as an opportunity for those persons engaged in science, technology and innovation to reflect upon their actions and think about the longer-term outcomes (be it only forty years down the road) that may stem from today’s decisions. In this way scenarios offer a means for “reflexive governance” (Barben, Fisher, et al. 2008) to consider your own actions and to understand how those fit (or don’t fit) within the current systems and to understand where this might be headed. Stories about the future offer a means to discuss the social and ethical implications of emerging technologies. Scenario narratives (that are defensibly plausible) can augment course curricula in science and engineering ethics courses, such as those discussed by McGregor & Wetmore (2009). In these ways, the goals set forth by the study have been met yet, much work remains.

This chapter has the bandwidth to explore the methods and outcomes of the results, it lacks a comprehensive assessment of the scenario narratives and the future worlds within which they exist. Questions regarding the justness or fairness from a
Rawlsian perspective are unaddressed (Rawls, 1985; Cozzens, 2011). Additionally, a comprehensive sustainability appraisal is absent and could be performed using principles synthesized by Gibson (2006) or Kemp et al (2005) or Grunwald (2004) or using a framework that specifically draws upon normative principles and is conjoined with innovation process.

The scenarios presented really serve as a set of ‘pre-engagement’ materials, as described by te Kulve & Rip (2011) for larger discussions on responsible innovation and civic engagement in science, technology and innovation policy. Work remains to bring these and other scenarios into the public sphere through visualization and planning tools through a design studio course titled, *Design Thinking, Sustainability, and the Future of Nanotechnology in the City*, which used film and rich forms of digital media to design the future city of Phoenix in 2050. Urban centers around the world are shaping emerging technologies, such as nanotechnology, and these cities need to consider: What are they creating and what are the plausible implications in the future? Significant work remains in using these scenarios as a ‘pre-engagement’ tool and drawing upon visualization and planning tools to shape a sustainable future for Phoenix.

**Addendum A**

1. **Scenario Narrative - Will the sun rise in Arizona? How markets pull innovation**

*Rays of sunlight broke across Nancy’s bed. The window’s tinting melted away as the night’s sky transformed into a grayish-purple aurora in anticipation of sunrise. Nancy*
awoke. Another day to fight for solar energy had begun and the aroma of freshly brewed coffee awaited her. The sunrise had already triggered the responsive coffeemaker’s sensors. Nancy sipped her coffee and reviewed her notes displayed on the surface of her dining room table for the upcoming 2050 Arizona Town Hall. She scoffed – these meetings had been going on for more than a half-century, since before 2010. And where were they today? No different than 2010, maybe a notch hotter at night and water restrictions were being imposed, but the real lack of change was in the energy sector, the lifeblood of any city. The market price of solar had never quite caught up with the marginally decreasing price of nuclear, coal, natural gas and petroleum. There were a hundred reasons, a thousand little incremental changes in technology and policy that had advantaged the legacy energy providers and continuously crippled the solar industry. Many pointed to the little known ACC (Arizona Corporation Commission) – the decision-making body that sets Renewable Energy Standards for state-regulated electrical utilities in Arizona, a state with 360 days of full sun. A political action group had ensured path dependency and supported candidates that undermined the solar industry and quietly propped up the legacy energy providers (coal, uranium and natural gas extraction industries) historically relied upon by SRP (Salt River Project) and APS (Arizona Power Supply). A quick shower heated by solar-hot water mats on the roof, a technology over a hundred years old, really got Nancy’s blood boiling. She thought, “It is just so simple.” She got dressed and walked down to the Lightrail and watched the electric automobiles zipping along into Phoenix. “Damn it,” she thought, “they are all charged up with coal, natural gas, and nuclear power. Well, there goes the benefit of electric cars.” Traffic
backed up and two people got out of their cars to look at a car accident ahead. She boarded the train and arrived 45 minutes later at the downtown university campus hosting the Arizona Town Hall. It was drawing good media attention. Right outside the entrance, she saw a trusted ally, a local streamer. Streams offered live feeds to the public, as witnesses of truth. Nancy, a state-level legislative policy advisor, leaned towards the streamer, her eyes ablaze. She looked into the streamer’s camera and said, “Do you see what the problem is? We still are totally reliant on fossil based energy! We must find ways to tip the scales and drive the solar economy. Even here at this university they are still trying to create higher efficiency photovoltaic panels. But we don’t need more efficient panels. The current technology out there is good enough. We don’t need more research! We need to adjust to the new normal. The climate has changed. We need to revise the 2025 standards and force the utilities to build more solar projects. We need to train hundreds of people to install PV panels and then put them to work. Why do you think unions complain? - Because state subsidizes run out every year and the electrical workers are laid off - that is why. The market is so volatile. Those people in the state legislature want jobs and they don’t want the state to spend money in support of solar energy. If we use federal dollars to retrain the workforce, the state needs to get their act together and support the solar industry. What are we doing? There are disconnects. Disconnects between the federal government, the state, and here at the city level, we can’t bridge those gaps.” Nancy, her voice rough with frustration, continued, “There is no common definition of the problem across the broader society. Until everyone understands we have a problem, they won’t allow the government to act. Not here
anyway. With all the sun we have, this should be an easy issue, solar energy is good for national security, it increases energy diversity and it increases local employment. We should be the global leader, but we aren’t. The market failed us. Energy is not a market good.” Nancy sighed and walked onto the levitation platform that drew her up to the eighty-seventh floor for the meeting.
2. Scenario narrative - Citizens and cities: Collaboration via social entrepreneurship

The rain had started after midnight. Dark clouds gave the morning sunlight a grey hue. Jermaine awoke to the pungent aroma of creosote oils mixed with ozone – a smell that promised blooming wild flowers in the desert southwest. The open window let in light, fresh air and the sounds of friends and neighbors. Jermaine had worked late at the CORE (Collective Of Researchers and Entrepreneurs) facility yesterday. The Phoenix City Water Administration had provided CORE with a seed grant for $250 million dollars to create a pilot project. CORE was helping the City of Phoenix to address the remaining contaminated groundwater in the fractured bedrock – just north of the Sky Harbor Airport. The historical DNAPL (Dense Non-Aqueous Phased Liquid) plume had been created decades ago in the 1980s. This problem had been contained in the 1990s and then just left there. The affects of climate change (increased drought in the Salt, Verde, and Colorado watersheds) had prompted the city to revisit this long abandoned water reserve. Jermaine’s formal education and natural leadership characteristics made him an obvious choice to lead the CORE team during this project. He had not led a project of this size before. The CORE team was comprised of financiers, lawyers, citizens, advocate organizations, scientists, engineers, city water planners, and a rotating set of college professors and high school teachers from the local institutions. The CORE team took on challenges and entered problem-oriented competitions formally organized by federal, tribal, state, county, and city governments (all of whom held some power in metropolitan Phoenix). CORE team members did well financially, earning 150% of the
average citizens’ salary in Phoenix, but none were ever going to ‘make it big’. Then again, Jermaine had not chosen hydro-geological engineering to become rich. His family had been living on a contaminated site in Phoenix when he had learned more about it in a high school classroom. Even back then, in 2010, he had heard that nZVI (nanoscale Zero Valent Iron) could solve the problem, but the testing and evaluation never seemed to move forward and then stalled and that potential solution, nZVI, was abandoned. From then on he had committed himself to addressing the groundwater contamination that lay beneath his community – rife with low land values, high crime and a lack of investment in urban redevelopment. That had changed slowly over the years and the citizens and city had formed a steering committee to oversee a long-term transformation of the urban center – geographically aligned with the electric trolleys lines, which date back to 1893 and re-established in 2010. Now, in 2050, a diverse network of transit systems brought people from the outlying communities of Tempe, Glendale, and Scottsdale into the dense urban center of Phoenix. Jermaine’s walked to the kitchen. His slippers softly padded across the tile floor. His fourteen-year-old daughter sat outside on the terrace. She was bent over a steaming bowl of rice. Jermaine thought, “She has probably already run five miles and I am just getting out of bed. Well I am going to bike to work … that counts.” She turned, scowled at him and returned to her breakfast.
3. Scenario narrative – Controlled & securitized: Closing in on freedom

Ja’Qra awoke to the morning rays gently easing their way through the blinds. Rustling leaves filled the air. Her preferred setting ‘desert sunrise’ was programmed into HIS (Home Intelligence & Synchronization) system. HIS system synced every second with the CSM (Community Security Management) system. Those systems were responsible for Ja’Qra’s residence. The CSM system was in place throughout the valley. It updated the Maricopa Sheriff’s office every two seconds, ensuring - almost real-time security updates to the second. The additional second had saved taxpayers hundreds of millions, after incalculable spending in the wake of The Breach. The Breach was a dark era in Arizona’s history. It occurred in 2023 between March and September and resulted in an estimated four million illegal immigrants streaming through the state’s territory. The federal government, blamed exclusively by local media and politicians, had lost their right to defend Arizona’s border in a landmark Supreme Court reversal, overturning a 2012 ruling. Since the ACT (Arizonian for Citizens’ Transparency), a new piece of legislation that came into effect on January 1, 2024, all children were encoded with their social security number embedded in forty discrete codons of nucleotides (using synthetic G-A-C-T sequences) in each child’s genetic sequence. Ja’Qra validated her status as awake and active in HIS system bathroom sink monitoring station. Her routine was soothing. She depressed her hands in a semi-solid gel that filled HIS system bathroom sink monitoring station. It massaged her hands, lightly scrubbed the skin, cleansed the skin and applied a novel daily nail polish pattern. All the while painlessly extracting 10
to 20 dead skin cells to verify Ja’Qra’s identity. HIS system reported this activity, as well as every other activity on the premises to the Maricopa Sheriff’s central security office and to Ja’Qra’s personalized healthcare management database per the ACT. The reason to report all activity for security reasons was obvious, no one wanted another Breach. The medical reporting mandates required by the ACT were more complicated. To support and fund a fully integrated and financially solvent personalized medicine program in Arizona required full participation by all residents to build the database of genetic diseases. Full citizen participation also provided the baseline health information from which illnesses could be identified as anomalies and treated in a preventative manner. Ja’Qra couldn’t remember all the reasons for the ACT, but she dutifully reviewed the prescribed daily health reports and consumed the MEAL (Medically Effective And Lovable) for breakfast. Her day had just begun, yet she felt fully prepared for her day at the CAMPUS (Central Academia of Memorization at Phoenix Unity School) and excited for the big football game tonight between her CAMPUS and their rivals – the Scottsdale Business and Engineering Academy.

A pale ashen sky gave way to streaks of magenta and lilac. The sun’s rays awoke, emanating from behind the Superstition Mountains. L’yan, one of millions of late night revelers, meandered home through Phoenix from the Wednesday night hacker event. L’yan only had a short walk through the early morning dawn to her building. She had spent the night with three friends at their conjoined apartments in a nearby pad. Their small group, along with 10,000,000 fellow hackers, beat the challenge posted on the PATHWAY (Privileged Access - The Hacker WAY) challenge board. L’yan shivered, a cool wisp of air and the feeling of success washing over her. This week’s PATHWAY challenge had been rather simple, but the implications had been important. Researchers in a government laboratory had created the genetic prototype for Grey Goo, a legacy threat, conceived of by science fiction writer Michael Crichton and taken seriously by risk and security experts for decades. This week’s PATHWAY challenge had had a singular mission – create a defense system robust enough to handle a global, simultaneous, outbreak of Grey Goo. The United Nations Security Council, limited by their static budget, had created an interface, called Sedna, accessible for hackers to enter and engage in PATHWAY challenges. Sedna was not just another form of cloud computing, but it was a distant and remote reality, an entire virtual world, within which dangerous and lethal threats could be assessed and initial mitigation efforts tested. Sedna, named after the furthest planet from the sun, was distant enough to be safe and exclusive enough that only the 10,000,000 (plus or minus) PATHWAY hackers could
attempt the challenge. L’yan had gained PATHWAY access during her thirteenth year of learning in the online ACADEMIA (Academy for Critically Adaptive trans-Disciplinary Engineering, Mathematics, Informatics, & Arts). She dropped out after that. Who needed a doctorate if you had hacker access to PATHWAY challenges? That was where the money was. Research funds were no longer tied up in the staid, traditional, disciplinary colleges and universities. In Phoenix, akin to many innovation centers around the world, social stratification was not determined by ability, race, gender, or family wealth. Stratification was based on your skills in problem solving and adaptive learning; your power to construction and shape materials; to write and decipher computer code; to hack and reap the rewards. L’yan’s place was posh, compared with ‘squares’ - people that either didn’t spend the time or didn’t have the skills to improve their condition through hacking. She lived on the top floor of an ever growing and changing building. L’yan had to continuously compete to stay on top. Gardens and waterfalls attracted birds, bats, and bees to the mid-air oasis. Phoenix, renewed by the ideals of individual freedom and independent creativity, had amended their building codes to allow the new hacker pads in 2035. Pads, served as the basis of innovation and growth. City leaders saw them as the keys to the Phoenix economy. Today, in 2050, ‘squares’ still live in relics, detached houses, off-pad. They constitute the labor force for the service industries that support the core pads at the urban core of Phoenix. Joseph Gammage, the security guard, smiled and waved as L’yan walked into her building.
Chapter 5

Nanotechnology for Sustainability: What Does Nanotechnology Offer to Address Complex Sustainability Problems?

1. Introduction

Nanotechnology is often touted as an important contributor to sustainability. Nobel laureate Richard Smalley (2006) spoke highly of nanotechnology’s potential to cope with global challenges such as energy production for a growing world population. Karn (2005) states similarly high hopes that “nanotechnology can help with all these sustainability [...] issues,” including climate change, resource depletion, population growth, urbanization, social disintegration, and income inequality. Diallo et al. (2011) acknowledge that “global sustainability challenges facing the world are complex and involve multiple interdependent areas,” but assert that nanotechnology is capable of mitigating many of those. Weiss & Lewis (2010) reflect sentiments of the American Chemical Society in recognizing the “significant contributions that nanoscience is making toward sustainability.” In light of these statements, it seems fair to conclude that Smith & Granqvist (2011) summarize a widely held position when stating: “Solutions to the urgent challenges of environment degradation, resource depletion, growth in population, and cities, and in energy use, will rely heavily on nanoscience.” Even when the complexity of sustainability challenges is enumerated and the socially embedded nature of technology is acknowledged, nanotechnological optimism and even determinism prevail.

Such claims seem to align with the concept of sustainability science, an emerging
field that is problem-focused and solution-oriented toward the long-term vitality and integrity of human societies (Kates et al., 2001; Clark & Dickson, 2003; Komiyama & Takeuchi, 2006; Jerneck et al., 2011; Wiek et al., 2012a). Over the last decade, sustainability science has laid theoretic and methodological foundations to comprehensively address ‘‘wicked’’ sustainability problems in light of systemic failures (Ravetz, 2006; Seager et al., 2012; Wiek et al., 2012a). However, the claims and related studies above generally fail to acknowledge that sustainability problems are neither simple nor merely complicated, but are rather truly complex in structure—and thus require a complex approach to resolution. Such an oversight has multiple origins. First, analysts sometimes confuse sustainability problems with such natural resource problems as energy supply or water contamination, thus neglecting such numerous non-biophysical challenges as epidemics, violent conflicts, or economic exploitation that equally threaten human societies and are often fundamental to or accompany natural resource problems (Jerneck et al., 2011; Wiek et al., 2012a). Second, there is a lack of consideration given to the root causes of sustainability problems. For example, by means of nanotechnology to remediate water contamination is a typical ‘‘end-of-pipe’’ solution, which, while necessary, is doing nothing to stop the proliferation of Superfund sites that are often concentrated in low-income and minority communities (Lerner, 2010). Third, nanotechnological solutions are often proposed as technological fixes without seriously considering alternatives. Yet, case studies demonstrate that other, non-technical solutions might be more effective and efficient (Sarewitz & Nelson, 2008). Fourth, potentially negative side effects of these nanotechnologies are seldom considered. This is a
particularly critical issue when addressing wicked problems, which often stem from previous solutions (Seager et al., 2012). Fifth, these studies suggest real progress although they usually focus on potential innovations to address the problem. Hypothesized impacts bias the perception of nanotechnology’s real contribution to sustainability and draw attention away from urgent sustainability problems that nanotechnology might not be capable of mitigating or away from better positioned mitigation strategies. With the promise of substantial economic gains and increased sustainability-related awareness of consumers, a sixth origin could be the use of sustainability claims as pure marketing strategy similar to “greenwashing” campaigns (Jones, 2007).

Sustainability problems are not just any kind of problem, but feature specific characteristics (Wiek et al., 2012a). They threaten the viability and integrity of societies or groups; they are urgent, requiring immediate attention for decisions to avoid irreversibility; they have projected long-term future impacts that necessitate consideration of future generations; they are place-based, which means causes and impacts can be observed within distinct localized area; they exhibit complexity at spatial levels (reaching from local to global levels) and cut across multiple sectors (social, economic, environmental); and they are often contested. Thus, complex sustainability problems are unlikely to be solved in the simple sense that a hammer can solve the problem of a nail sticking out—even considering the sophistication of hypothesized nanotechnologies. Instead, we use the language of mitigation to refer to interventions intended to ameliorate complex sustainability problem.
In light of these potential pitfalls, the study presented here conceptualizes sustainability problems as complex constellations (networked cause-effect chains) that present potential intervention points, amenable to different types of solution options. The study relies on interdisciplinary workshops and literature reviews to appraise specific contributions of nanotechnology to mitigating sustainability problems with four questions in mind:

1. Are all sustainability problems amenable to nanotechnological fixes? Which ones are and which ones are not?
2. How and where does nanotechnology intervene in such problem constellations?
3. Are nanotechnological solutions more effective and efficient than alternative mitigation options? Are there any potentially negative side effects associated with nanotechnological fixes (as experienced with other technological solutions)?
4. What is the evidence that the potential of nanotechnology for mitigating sustainability problems is being realized through actual implementation?

The study focuses on nanotechnologies designed to contribute to sustainability efforts, including applications for increasing the efficiency of solar panels, water purification, air purification, environmental remediation, etc. It is important, however, to recognize that these “green” uses represent less than 10% of nanotechnology applications currently patented (Lobo & Strumsky, 2011).

There is ample room here to select exemplary cases of historic claim making and
subsequently create a hypothetical space to explore the nanotechnology claims as rhetoric bent on exhibiting nanotechnology’s potential. Rather than taking that road, this study addresses the outlined questions in a specific context, namely, the urban context, within which we analyze the sustainability claims (cf. Jones, 2007). Urban locales, containing more than 50% of the world’s population, are confronted with urgent sustainability challenges, and cities have started to take action on these challenges independently (Svara, 2011). Cities are also the key hubs of innovation, as well as decision-making centers for larger regions, states, and nations. Their infrastructure, culture, and technological developments—embodied in a dynamic set of resources, institutions, and actions—represent society’s general development path.

Phoenix, recently granted the disreputable distinction of being the world’s least sustainable city (Ross, 2011), is an excellent case for intervention research on urban sustainability problems. The commitment to a sustainable future and a strong partnership between researchers, city planners, and citizens has been developing since 2009, resulting in a sustainability-oriented draft General Plan with several accompanying and follow up projects (Wiek et al., 2010; Wiek & Kay, 2011). We build on these endeavors when exploring nanotechnology’s potential in more detail for three exemplary urban sustainability problems prevalent in Phoenix: two obvious ones, water contamination and non-renewable energy supply, are presented along side one urban sustainability problem less obviously addressed (but claimed to) by technological solutions, childhood obesity. The selected issues receive considerable attention in scientific and political communities as recently summarized by Roco et al. (2011, pp.11) "Global conditions that might be
addressed by mass use of nanotechnology include [...] constraints on using common resources such as water, food, and energy.’’

Our ultimate goal is to perform research that embeds nanotechnology in a suite of potential solutions to urban sustainability challenges that warrant consideration and assessment by experts and stakeholders. In doing so, the study contributes to anticipatory governance of emerging technologies in general, and nanotechnology in particular, through the lenses of urban systems and sustainability science (Barben et al., 2008; Guston, 2008; Karinen & Guston, 2010; Wiek et al., 2012b; Wiek et al., 2013).

2. Research Design

In this study, we conceptualize nanotechnology as the supply-side (technological solution options) to sustainability problems as the demand-side (societal needs). This supply–demand model follows Sarewitz & Pielke’s (2007) proposed framework to assess a given technology (supply) with respect to a given societal need (demand) through an economics metaphor. The goal is to identify the overlap between demand and supply, or in other words, reconcile to what extent demand for solutions to sustainability problems and supply of nanotechnology match (Sarewitz & Nelson, 2008), and thus to what extent we might reasonably expect nanotechnology that is currently being produced to contribute to their mitigation. Existing and proposed nanotechnologies have the potential to address a spectrum of challenges, but defining the overlap between demand and supply means identifying how nanotechnology ‘‘solves’’ specific problems with what impacts (intended and unintended), and whether or not other, more effective, efficient, or equitable alternatives exist (Wiek et al., 2013).
To investigate specific intersections, we adopt basic ideas of intervention research methodology (Fraser et al., 2009), namely to evaluate the effectiveness of strategies for positive change (improvements of social conditions). Accordingly, each nanotechnology application is considered a unique intervention into a complex problem constellation. We apply this methodology to appraise the effectiveness of exemplary nanotechnologies to mitigate urban sustainability problems. Previous technological interventions in complex socio-technical systems, such as cities, have not always led to the desired outcomes, and so it is also important to account for unintended consequences in the appraisal (Wiek et al., 2013).

We conducted this study in three phases by means of a case study approach that relied on a set of mixed methods. The first phase began with initial literature reviews on urban sustainability challenges (demand) and nanotechnology applications (supply). We then conducted two expert workshops to deepen the supply–demand knowledge base through an exploration of urban challenges in metropolitan Phoenix (see case study details in the following section). One workshop was conducted with an interdisciplinary group of scholars (n = 13) from geography, urban planning, social sciences, civil engineering, and sustainability science with expertise in urban systems, transportation, energy systems, climate change, justice, poverty, and resilience. Participants generated a ranked list of sustainability problems and outlined for each of the ten highest ranked problems the problem constellation of root causes (drivers), causing activities, perceived benefits, negative impacts, and affected populations. The other workshop was conducted with an interdisciplinary group of scholars (n = 9) from physics, chemistry, electrical
engineering, materials science, and energy systems engineering. The workshop validated and augmented materials gathered through the nanotechnology literature review. The participants ranked the nanotechnology solutions that would most likely contribute to urban sustainability.

The second phase of the research consisted of in-depth literature reviews to substantiate the nanotechnology applications and urban sustainability problems elicited in the expert workshops. One was a review of literature, documents, and datasets that provide evidence of specific urban sustainability problems in metropolitan Phoenix. The final literature review was a reconciliatory analysis of the amenability of technological solutions to sustainability problems. Specific quantitative evidence, estimations, and data were explored that apply to both the potential benefits and life cycle costs of selected nanotechnologies.

The third and final phase of the research was a set of three walking audits and reflections with a group of nanotechnology researchers (engineers and social scientists) and community members (n = 20) in the case study area (see description below). The walking audits explored the intersection of nanotechnologies and urban sustainability problems, focusing on water contamination, energy systems, and the food-health nexus. Participants discussed the prospect, possibility, and impact of nanotechnology interventions at specific places where those urban sustainability problems manifest.

In summary, we employed a case study approach (focusing on exemplary sustainability problems in a neighborhood in Phoenix) and gathered relevant data from literature and document reviews, as well as expert workshops and walking audits through
participatory research. The results integrate evidence from published studies and official documents with insights from community and subject matter experts.

3. Case Study: The Gateway Corridor Community in Phoenix, Arizona

In order to make the research more tangible, accessible, and relevant to stakeholders and decision-makers, we conducted a case study following the paradigm of place-based sustainability research (Wiek et al., 2013). Based on a previous study (Wiek & Kay, 2011), we selected the Gateway Corridor Community in metropolitan Phoenix for this study (see Fig. 1). The community name is not an official title but reflects the transportation and infrastructure corridor (coupled light rail, airport, automobile, and canal) with the Gateway Community College as central hub. The community is bounded to the north and east by state highways 202 and 143, to the south by Sky Harbor International Airport and to the west by 24th Street. The area is bisected from northwest to southeast by the Grand Canal with the only canal crossings at Van Buren Ave and Washington Ave. The community comprises industrial, commercial, educational, cultural, and residential areas. Recent socio-demographic data indicate that, of the 5,096 residents, 66% are Hispanic or Latino (USCB, 2010a). The American Community Survey (ACS) identifies that 43% of the population earns below established poverty levels, median household income is $33,392, and one-third of residents (33%) do not have high school diplomas or equivalencies (USCB 2010b). These data provide a limited snapshot of the community; yet, they indicate significant needs and barriers to sustainable community development.
The selection of the Gateway Corridor was based on two factors: the diverse set of urban sustainability problems and the engagement in numerous intervention activities by university, city, and civic entities. The Gateway Corridor Community exhibits many of the sustainability challenges identified by the expert workshop, including: minimal economic opportunities for residents, reflected in underinvestment in building stock and deteriorating industrial base; a lack of amenities accessible by walking or cycling; urban heat island effects due to lack of vegetation cover and choice of construction materials; social isolation between the diverse (ethnic) sub-communities in the area; and historic groundwater contamination from industrial production. In response to these challenges, several synergistic efforts are underway in the area, including transit-oriented development along the new light rail route through the ‘‘Reinvent Phoenix’’ project.
funded by the U.S. Department of Housing and Urban Development (HUD) (Johnson et al., 2011), energy efficiency efforts for the built environment through “Energize Phoenix” funded by the U.S. Department of Energy (DOE) (Dalrymple & Bryck, 2011), high-tech economic development in the area (Discovery Triangle, 2011), proposals seeking to reinvent the water utility-oriented Grand Canal (Ellin, 2009), Phoenix’s General Plan update process, which brings citizen input to bear on the planning process (Wiek et al., 2010), and plans for a new community health care center expanding services into the community.

4. Results

4.1. Urban sustainability problems (demand). Applying the concept of complex sustainability problems outlined above, experts identified a set of urban sustainability problems for metropolitan Phoenix, including lack of satisfactory economic opportunities, non-renewable and inefficient energy systems, automobile reliant mobility, poor air quality, overuse of water resources, environmental injustices, childhood obesity, waste, lack of social cohesion, and urban heat island effects. The experts then initially explored the root causes (drivers), causing activities, perceived benefits, negative impacts, and affected populations. The detailed results of the workshop are presented elsewhere (Wiek & Foley, 2011) and will be captured in an interactive database of urban sustainability problems (syndromes). We selected three of these urban sustainability problems for illustrative purposes here. The first two—water contamination and non-
renewable energy supply—are seemingly amenable to technical solutions. The third, childhood obesity, appears not to be, and yet, emerging nanotechnology applications promise to address (childhood) obesity, too. We further analyzed the selected urban sustainability problems with respect to root causes (drivers), causing activities, perceived benefits, negative impacts and affected populations, based on expert input, recent study results (e.g., Wiek et al., 2010; Ross, 2011; Svara, 2011), and specified for the Gateway Corridor Community (as far as data were available). The key information on the three problem constellations is summarized in Table 5.1.

4.1.1. Water contamination. Stakeholders and researchers alike define the Motorola 52nd Street (M52) Superfund Site as an urban sustainability problem, literally underlying the community. The Motorola semiconductor facility acknowledged the release of an estimated 93,000 gallons of tri-chloroethylene (TCE) in 1982 (ADEQ, 2006). Numerous chlorinated and non-chlorinated hydrocarbons are found at the M52 site, but the 93,000 gallons of TCE is the only published estimate. The primary causes of the TCE releases were attributed to leaking tanks, improper hazardous waste disposal into on-site dry wells, and poor chemical management during the production of industrial goods. These were common practices in semiconductor and metal-working facilities across the country (EPA, 2011b). At the M52 Superfund Site, TCE migrated to the aquifer running west to east along the Salt River that flows directly beneath the Gateway Corridor. It is one of the only confirmed dense non-aqueous phase liquid (DNAPL)-contaminated fractured bedrock site beneath a large urban center. It is divided into three operable units (OU1, OU2, and OU3). OU1 and OU2 underlay the Gateway Corridor
case study area (EPA, 2011b). Root causes included cost cutting measures (the lack of preventative tank maintenance, improper disposal, and employee training on chemical handling); the absence of anticipatory chemical management regulations (before 1980); the perception that dry well disposal was a safe chemical management practice; and the drive to produce inexpensive electronics to support profits and national competitiveness. Inexpensive electronics meet deeper societal root causes such as consumer value, convenience, and utility maximization.

Adverse effects include an estimated 800 billion gallons of contaminated groundwater with unmeasured impacts on alluvial-based biota. Ingestion exposure risk for people was mitigated through the installation of city-provided drinking water (from surface water). Residents recall playing in contaminated water as children and complain of high cancer rates in families living in the community, but cancer cluster research has not produced statistically significant correlations (ADEQ, 2011). Soil gas vapors, previously not considered a substantive risk, are migrating up from the fractured bedrock and alluvial soil layers, eventually intruding concrete foundation slabs of residents and businesses. Recently collected data validated by EPA, in an area adjacent to Gateway Corridor, show that more than 50% of soil gas samples exceed the current risk-based screening levels (EPA, 2011c). More recently, indoor air quality testing shows elevated chlorinated hydrocarbons derived from groundwater contaminants in 15 of 39 residences (EPA, 2011d). This presents a direct inhalation risk to residents and workers and has triggered an extension of the indoor air quality testing. Citizens had implored state agencies, for years without success, to test soil gas vapors—until EPA assumed control of
vapor intrusion and community involvement.

Twenty-eight years of poor information, unresponsive state agencies, and corporate-led remediation efforts fueled feelings by residents that there is an industry-agency alliance. Community members repeatedly questioned researchers conducting community surveys, for fear they represented government or corporate interests. This history of mistrust now plagues the ability of the regional EPA, while based in San Francisco, to operate in Phoenix. EPA cannot dedicate the requisite resources to rebuild community relationships and trust due to budgetary constraints. Diverse publics living in the Gateway Corridor are not well represented in the community involvement group meetings. The Hispanic and Latino community faces a racially biased state immigration law, enforced in a manner recently deemed discriminatory by the US Justice Department (USDOJ, 2011). This penumbra of discrimination overshadows attempts to bring the community (en mass) to public meetings. The M52 Superfund Site depresses local property values, as owners are required to disclose this fact to potential buyers, and undermines the City’s property tax base. The M52 Superfund Site is not merely a natural resource or environmental justice issue, but is central to a larger constellation of causing activities, root causes, and effects (see Figure 5.2).
**Table 5.1**

*Basic Structure of Urban Sustainability Problems*

<table>
<thead>
<tr>
<th>Title</th>
<th>Causing Activities</th>
<th>Underlying Drivers and Actors</th>
<th>Adverse Effects (AE) and Impacted Populations (IP)</th>
<th>Prevalence Indicators and Sources</th>
</tr>
</thead>
</table>
| Water Contamination    | Industrial production of goods | Reactive government policies; lax standards for industrial production and accountability; perception of safety; lack of consumer activism; values of comfort; values of utility maximization and specialization | AE: Impacted groundwater, impacted air (vapor intrusion); biological impacts; exposure risks (ingestion & inhalation); decreased property values; decreased trust; geographic stigmatization  
IP: Residents (vulnerable communities and societal groups), city administration (lost tax revenue), state and federal governments (remediation expenses) | Gallons of groundwater contaminated at M52 site: unknown (annually >1 billion gallons are pumped and treated) Gallons of toxics released at M52 site: unknown (93,000 gallons estimated in one report – ADEQ 2006).  
Acres of land atop contaminated groundwater (M52 site): 7,300 acres (EPA 2011a) People living on M52 site: 52,233 in that overlay site from McDowell to Buckeye & 7th Av to 52nd St (USCB 2010) |
Childhood Obesity

Malnutrition (convenience foods); Lack of exercise; Food deserts; industrial agriculture practices and policies; large-scale production and distribution system; marketing and branding foods; low recreational opportunity; values of convenience, comfort, and safety; lack of knowledge; economics

AE: Early on-set diabetes; cardiovascular diseases; psycho-social impacts; future educational opportunities and earning potential decreases; increased healthcare costs; increased morbidity and mortality
IP: children, especially racial minorities and lower earning socio-economic; parents of obese children; society (supporting healthcare and lost productivity).

Percentage of overweight and obese children (16yrs and older) (BMI >85th Percentile) in Arizona: 17.8 (Singh et al., 2010) Mean hours/week physical exercise for children ages 14-18 in Arizona: >33% exercise less than once per week. [AzDHS recommendation: 100% of children exercise most days of week (5 of 7 days)]
Adults eating fruits (2) and vegetables (3) in Arizona: 30-34.9% eat fruits, 20-24.9% eat vegetables (Grimm et al 2010) [AzDHS recommendation: 100% of population consume fruits and vegetables (5) servings combined (AZDHS 2006)]
Average daily intake of fats & oils as nation: 179g (1,600 calories) (Hiza & Bente 2007) [USDA/HHS recommendation: 25-35% of caloric intake or 500 to 1,120 based on recommended caloric intake below]
Average caloric intake per person as nation: 3900cal (Hiza & Bente 2007) [USDA/HHS recommendation: 2,000 calories per person per day, up to 3200 in adolescent males]
Non-renewable Energy Supply

Centralized production, distribution and use of fossil and nuclear energy

Centralized planning; high consumption based on potentially unlimited supply; subsidizing fossil fuels; lack of knowledge about alternatives; larger homes and dwelling creating demand; rural electrification policy; culture of electrical consumption; path dependency; full life cycle costs not incorporated; building codes

AE: Vulnerability to power outages, based on dependence for heating, cooling, cooking, and water; decreased visibility; DALYs from poor air quality; increased carbon dioxide emissions; mining and extraction impacts; transmission impacts

IP: Lower socio-economic groups; workers with direct exposure; children (lung development); elderly (increased stress on lungs)

Total Tons of COE/GDP: 4.95 MMTCO2E in Arizona (estimate) by ACCAG 2006

COE/capita: 7.0 MMTCO2E (estimate) by ACCAG 2006

Electricity Energy Production as Percentage of COE generation in Arizona: 38% (ACCAG 2006)

Percentage of renewable energy in Arizona: 2.8% (not including hydropower) 6.2% (including hydropower) (ACCAG 2006)
4.1.2. Childhood obesity. The network of severe individual and societal impacts, as well as their intermediate and root causes, constitute childhood obesity as a complex global problem (Finegood et al., 2008; Brennan et al., 2011). Based on rudimentary data, childhood obesity is considered a prevalent problem in Arizona, where 17% of children were obese and 30% overweight in 2007 and which suffered the highest rate of increase in obesity (46%) between 2003 and 2007 among all states (Singh et al. 2010). Obesity arises from two primary causing activities, a lack of exercise and overconsumption of (malnutritious) foods. A diverse set of root causes, including environmental and social factors, underlies these behaviors in the case study area (Wiek & Kay, 2011). Residents in the Gateway Corridor must travel north under state highway 202 to get to the preferred shopping markets, Walmart and Food City. The only food stores within walking distance of residents are convenience stores and fast-food restaurants. (The Chinese Cultural Center within the case study area boundaries offers both dining and grocery services, but they are not preferred by many non-Asian community members.) Industrial-scale agricultural production, processing, and distribution networks supply large grocers, who provision low-cost and low-quality foods. Marketing and branding efforts successfully draw people into purchasing processed foods that are high in fats and oils. Transporting food by public transit in Phoenix’s summer heat, with minimal shading structures for pedestrians, reinforces a reliance on automobile transportation and values of convenience. With highways and the airport walling the community off, the only unbarred path for foot traffic is west toward the state prison facility at 24th and Van Buren. Inmates in bright orange jumpsuits are seen through mesh fences confined in their yard. This stretch of Van
Buren, Washington, and Jefferson avenues running west is known locally for prostitution, hourly motel room rentals, pornography stores, strip clubs, and narcotics distribution. Perceptions of roads and local canals as dangerous for children encourage indoor recreational activities. Local students often travel to the YMCA facility for safe and indoor recreation opportunities. There are no public parks in the Gateway Corridor and there are currently no plans to construct parks in the vacant lots due to shrinking city budgets.

Adverse effects, studied in comparable urban areas, range from increased morbidity and mortality to early onset type II diabetes to foot and knee pain that reduces mobility to psycho-social impacts observed in children and adults (see Dietz, 1998; Freedman et al., 2005; Finegood et al., 2008; Biro & Wien, 2010). The prevalence of childhood obesity is elevated in communities of color with African Americans and Hispanics having more than twice the likelihood as non-Hispanic white children (Singh et al. 2010). Macro-economic impacts are projected to reach an annual cost of $10 billion in 2035 in the United States (Lightwood et al. 2009).

4.1.3. Lack of renewable energy supply. Residential and commercial energy needs are met through a centralized production and distribution network. Arizona Public Services Co. (APS) provides electricity to residents in the Gateway Corridor with the following energy portfolio: 38 % coal, 27 % nuclear, 30 % natural gas, 3 % renewables, and 2 % energy efficiency (APS, 2012). APS released their projected energy portfolio for 2025 revealing a 1 % decrease in coal and nuclear. Natural gas is estimated to increase 33 % and renewables and energy efficiency by 600 % (APS, 2012). The primary
development need expressed by APS officials is transmission capacity. A plan shows redundancies in centralized networks are emphasized through 2020 (APS, 2011). This reflects root causes including, growing societal demand, path dependency in the infrastructure, electrical device connectivity, and standardization policies. Adverse effects include anthropogenic-based climate change with various subsequent effects such as water shortages in the desert southwest (Seager et al., 2007). Second, localized urban heat island effects are most likely to affect Hispanic residents and those in the Gateway Corridor (Chow et al., 2012). The electricity system from source to outlet encompasses sectorial dimensions of economics, natural resource, and social demands detailed in Table 5.1.

4.2. Nanotechnology (supply). A broad literature review yielded a number of nanotechnologies directly applicable to urban sustainability problems. We validated the initial set of applications through expert workshops and interviews, which yielded a top ten list of nanotechnologies that held promise to alleviate urban sustainability problems in metropolitan Phoenix. From this set, we selected those applications that are pertinent to the three urban sustainability challenges described above. Table 5.2 reflects those applications, also captured in an online database entitled ‘‘Nanotechnology in City Environments’’ (NICE) that serves as a repository for information on the functionality, as well as the sustainability challenges these technologies are seeking to ameliorate and information on potential benefits and risks (http://nice.asu.edu).
Table 5.2.

Profiles of Nanotechnologies Applicable to Selected Urban Sustainability Challenges

<table>
<thead>
<tr>
<th>Urban Sustainability Challenge</th>
<th>Nanotechnology Function</th>
<th>Nanotechnology Structure or Substance and Mechanism</th>
<th>Potential Full-Scale Benefits</th>
<th>Potential Full-Scale Life Cycle Impacts</th>
<th>Development Stage</th>
<th>Substitute for:</th>
<th>Sources/References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water contamination</td>
<td>Water Decontamination</td>
<td>nZVI particle; Active</td>
<td>nZVI is injected within a slurry to catalyze organic-based chlorinated solvents within groundwater (ie. in situ)</td>
<td>Unknown, life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2011).</td>
<td>Engineering</td>
<td>Pump and treat methods with activated Carbon</td>
<td>Watlington 2005; Zhang 2005; Valli et al. 2010; EPA 2011c</td>
</tr>
<tr>
<td>Water contamination</td>
<td>Water Desalination</td>
<td>Polydimethylsiloxane compound; Passive</td>
<td>Ion concentration polarization creates functional junction to separate desalinated water from enriched brine</td>
<td>Unknown, life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2011).</td>
<td>Scientific Proof of Concept</td>
<td>Macro-porous filters and evaporators</td>
<td>Kim et al. 2010; Tarabara 2010</td>
</tr>
<tr>
<td>Air contamination</td>
<td>Air Purification</td>
<td>Carbon Nanotubes (CNTs) and TiO2; Passive Cleaning all indoor air to remove contaminants</td>
<td>Unknown Some evidence of lung impacts from air borne CNTs (Kimbrell 2009)</td>
<td>Scientific Proof of Concept</td>
<td>Woan et al. 2009; Oh et al. 2009</td>
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<tr>
<td>Air contamination</td>
<td>Vapor Detectors</td>
<td>SnO2 Metal Oxide; Passive Contaminant gas surface reaction with metal oxide senses presence and abundance of contaminant in air</td>
<td>Unknown, life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2011).</td>
<td>Engineering Electro-chemical gas sensors with bulk material surfaces</td>
<td>Graf et al. 2006; Wang et al. 2010; Waitz et al. 2010</td>
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</tr>
<tr>
<td>Health Additives</td>
<td>Food Additives</td>
<td>TiO2 Particle; Passive Titanium Dioxide offers a transparent coating that prevents a broad spectrum of ultraviolet light from penetrating</td>
<td>Oral ingestions of TiO2 particles in lab mice has lead to health concerns about bio-distribution and acute toxicity (Wang et al. 2007)</td>
<td>Commercial Shelf-life expiration and product disposal</td>
<td>Mihee et al. 2007; Wang et al. 2004; Kuzma and Verhage 2006</td>
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<tr>
<td>Energy efficiency</td>
<td>Energy Storage</td>
<td>Fluorinated polymers (FPA) and Alkaline metals; Active</td>
<td>Full-scale installation could produce large capacity energy storage with denser and non-aqueous (ionic air) electrolyte.</td>
<td>Unknown, life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2011).</td>
<td>Scientific Proof of Concept Aqueous phase electrolyte solutions.</td>
<td>Friesen and Buttry 2010; Salloum et al. 2008; Mickelson 2011</td>
<td></td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Photovoltaics</td>
<td>CdTe or GaAs; Passive</td>
<td>Full-scale installation could produce the power required by Phoenix, but storage and intermittency are pending</td>
<td>Life cycle CO2 equivalent emissions estimated at 14-9 g-C/kWh and 90-300 times lower than coal fired power plant in studies (Fthenakis et al. 2008).</td>
<td>Ubiquitous, but not available</td>
<td>Fossil, nuclear, and biomass combustion</td>
<td>Kato et al. 2001; Noufi and Zweibel 2006; Tettey et al. 2010</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>Industrial Catalysis</td>
<td>Zeolite L Particle; Active</td>
<td>Zeolite L nanoporous catalyzes bulk particles into reformed compounds</td>
<td>Unknown, life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2011).</td>
<td>Scientific Proof of Concept</td>
<td>Bulk Catalysts</td>
<td>Hu et al. 2011; Bernardo et al 2009</td>
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<tr>
<td>Energy Efficiency</td>
<td>LED Lighting (nano-enhanced)</td>
<td>Nonacene compound; Passive</td>
<td>Organic light emitting diodes that can be affixed by printing on materials surface</td>
<td>Proposed research on-going at Green Launching Pad (Brooks 2011).</td>
<td>Scientific Proof of Concept</td>
<td>Inorganic LEDs &amp; current lighting elements</td>
<td>Purushothaman et al. 2011; Gao et al. 2011; Kaur et al. 2010</td>
</tr>
</tbody>
</table>

*Note. For further details visit: http://nice.asu.edu.*
4.2.1. Nanotechnology interventions in urban sustainability syndromes.

To this point, we have analyzed three critical urban sustainability challenges facing metropolitan Phoenix and identified ten nanotechnologies that offer technical solutions to these sustainability challenges. Based on this systemic problem understanding and functional knowledge of potential nanotechnology solutions, our next and final step is to appraise the interventions of nanotechnology solutions into each of the three problem constellations. Table 5.3 details the case, the intervention point, mechanism, governing decision-makers, the decision process, barriers to intervention, potential resources required to intervene, effectiveness and efficacy (if known) of the nanotechnology, and restates the current intervention. We present the results for our three case studies as an initial attempt to reconcile nanotechnology applications (as supply) and sustainability challenges (as demand) to exemplarily answer the guiding question on what nanotechnology offers to address complex sustainability problems.

4.2.2. Addressing water contamination. The latent decision (made in 1986) was to address remediation through pump and treat methods (EPA, 2011b). The annual average volume of water pumped per year between 2005 and 2010 was 844 million gallons in OU1 and OU2 (EPA, 2011f). The annual average volume of TCE recovered per year from OU1 and OU2 was 115 gallons (EPA 2011f). The recovery rate of TCE (gallons) per million gallons of groundwater pumped per year from OU1 and OU2 between 2005 and 2010 is 0.14 gallons of TCE. A linear extrapolation of the current TCE removal rate suggests that the complete removal of TCE will occur after the year 3000. This timeframe is untenable for current and future residents.
The M52 Superfund Site appears to be amenable to a nanotechnology solution as current pump and treat technologies are neither efficient nor effective. The efficacy rate of nanoscale Zero-Valent Iron (nZVI) to remove TCE at the Goodyear-Phoenix Airport site is reported at 82–96% in pilot tests (Chang et al., 2010). We must caution that the hydrology and geological structures at the Goodyear-Phoenix airport site are not directly comparable to the M52 site; however, these are promising results. The effectiveness for nZVI slurry jet injections into groundwater may eliminate the need for groundwater pumping. Three rounds of in situ nZVI slurry jet injections would theoretically reduce TCE (at 82% efficacy) to approximately 0.5% of current levels. From this rough appraisal, we can conclude that in situ remediation with nZVI may remove the TCE either sooner (in <1,000 years) and with less effort (pumping 844 millions gallons of groundwater annually). As for the filtration of contaminated air with CNTs, there is little evidence of in situ testing. Ideal conditions in laboratory experiments and placing devices in residences are different contexts. Significant work is needed to refine prototypes before testing CNT air filtration in non-laboratory settings.

There are issues with in situ nZVI slurry injections and CNT air filtration. First, the fate, transport, and toxicological assessments for both ecotoxicity and human health of full-scale application of jet-injected nZVI slurry have not been conducted. While deploying CNTs in residences to clean organic toxins from the air calls forth efforts to reduce fire risk with asbestos tiles. Ensuring asbestos-like nanoparticles are not released in homes is a critical issue (Philbrick, 2010). Thereby, a potential unintended consequence from injecting nZVI quantities sufficient to remediate billions of gallons of
contaminated groundwater could be anticipated, as could the release of CNTs into homes from design or user error. Second, the cost estimates to produce the quantities of nZVI slurry required to treat an estimated 800 billion gallons of contaminated groundwater or those for CNTs for filtration are not known. Net present value calculations discount any future benefits past 30 years to a value of zero, making the cost-benefit calculations appear negative. Current cost-benefit models that discount future generations will not support near-term and high-cost solutions. Further, the formalized decision-making structure, which cedes authority to EPA (with judicial review by the 9th Circuit Court), may further impede this intervention. Technical questions of the applicability of nZVI and CNTs aside, significant toxicological, financial, and decision-making hurdles remain.

Considering applied pilot-scale testing of nZVI slurry to remediate groundwater (EPA, 2011e; Watlington, 2005; Chang et al., 2010) and laboratory-scale application of CNTs, the evidence supports the rhetoric on environmental applications of nanotechnology (Karn, 2005) in this case. The proposed nanotechnology intervention, although certainly needed to optimize the current solution, occurs downstream of the original incident (release of TCE) as depicted in Fig. 5.2. The intervention will not address upstream policies, values, or resources that influence the actions that caused this historic release, including potential health impacts from nZVI slurry or CNTs. In fact, there are similar industrial practices that continue to create new suites of large-scale environmental challenges potentially analogous to superfund sites, e.g., oil spills, hydraulic fracturing in natural gas fields, and unregulated nanoparticle disposal.

When considering interventions in wicked problems, silver bullets lack the ability
to resolve all the complex problem elements (Seager et al., 2012). Rebuilding trust, co-
producing visions of the community (with researchers, city planners, regulatory agencies,
and citizens), and strategic investments in community assets are needed to transition the
Gateway Community toward a sustainable neighborhood consisting of vibrant businesses,
lively parks, and urban gardens—as expressed in visioning workshops (Wiek & Kay,
2011). A more profound approach would require a suite of interventions, including non-
technical (institutional) interventions. Educating students at the nearby BioScience high
school and engaging parents and administrators at Crockett Elementary School and
planners at Gateway Community College are ways to communicate these issues to the
next generation of citizens and decision-makers. Strategic planning efforts to co-construct
a future vision of the community between citizens, city planners, researchers, and
businesses are underway. A $10 M research proposal for long-term efforts toward
cleanup and community sustainability that explores technical and non-technical solution
options at the M52 Superfund Site is currently under review with the National Institutes
of Health.
4.2.3. Addressing childhood obesity. Childhood obesity is currently a highly publicized issue of public health concern. From the Office of the President (Barnes, 2010) to local parent and teacher associations, numerous interventions are being attempted. There are few evaluations of the effectiveness of these interventions (Brennan et al., 2011). The proposed nanotechnology interventions are twofold. First, the food packaging with TiO2 that allows industrial-scale agricultural production and distribution to reduce microbial contamination of vegetables for longer a shelf life. The industry presents this intervention as a means to overcome costs associated with product loss (spoilage) and allow for greater profitability in retailing fresh vegetables wrapped in TiO2-coated packaging (Robinson & Morrison, 2009). The second intervention is the construction of nutritionally enhanced carbohydrates (a food staple in US diets) with
omega-3 fatty acids (Robinson & Morrison, 2009). This intervention is intended to induce a compound that will confound adiposity development at the cellular level.

Neither intervention is cognizant of physiologic, socio-economic, or cultural preferences. Wang et al. (2007) shows that TiO2 ingested in laboratory animals is transported to a variety of organs, raising concerns of acute toxicity and biotoxicity. Omega-3 fatty acids are described as healthy fats at the rates currently consumed; however, current engineered methods to increase omega-3 levels are primarily observed in farm-raised fish. Elevated risks of mercury, organo-chlorine compounds, and polychlorinated biphenyls are being discovered in farm-raised fish (Hamilton et al., 2005; Domingo, 2007). This stirs the question of whether unintended compounds will join the engineered omega-3 fatty acids encapsulated in carbohydrates.

To shift perspective, who is the targeted market for engineered carbohydrates, longer shelf life vegetables that cost less than organic vegetables and wild caught fish? Studies indicate that consumers’ preference for engineered foods is lower than for non-engineered foods (Siegrist et al., 2007; 2009). Childhood obesity in the US is more likely in lower income groups (3.46 times), in neighborhood perceived as unsafe (1.61 times), in neighborhood with trash visible (1.44 times), and where no community recreation center is located (1.23 times) (Singh et al., 2010). The Gateway Corridor is primarily a low-income community that is perceived as unsafe, lacks a recreation center, and trash is visible on sidewalks and abandoned lots. This suggests that Gateway Corridor residents could be a considerable segment of the target market for products addressing childhood obesity, presumably against their preferences. The proposed nanotechnology
interventions reinforce practices and norms of industrial-scale agriculture and
distribution to automobile-oriented urban communities.

Residents and decision-makers have outlined more holistic and preventative
interventions in collaborative visioning workshops (Wiek & Kay, 2011). Such visions
include community organizations (schools, neighborhood associations, and faith-based
organizations) providing land for urban agriculture and skills training; a community
center that provides childcare services, adult education, after school recreational and
learning opportunities for all ages; and job and skill-oriented trainings offered through
voluntary work supporting community-based small business initiatives. Mountain Park
Health Center, a non-profit health care service provider, is funding community-based
participatory research to develop innovative, effective, and comprehensive health care
services together with the community. Administrators at both Gateway Community
College and Crockett Elementary School are engaging with parents, students, and
researchers to better understand the problems and devise solutions in concert, rather than
in top–down management fashion.
Table 5.3.

Nanotechnology Applications as Intervention Strategies for Complex Urban Sustainability Problems

<table>
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<th>Case Study</th>
<th>Systemic Intervention Points</th>
<th>Mechanism</th>
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<th>Barrier(s)</th>
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<tr>
<td>Water contamination (M52 Superfund Site)</td>
<td>Remediate contaminated groundwater Provision air filtration</td>
<td>Contaminant removal post-release</td>
<td>Regulators, responsible parties, community members</td>
<td>Formal federal decision-making process</td>
<td>Decision-making Process; Test site validation; Acceptance by parties; Sunk costs in current technology</td>
<td>Unknown energy and materials costs.</td>
<td>Pilot stage in situ testing for nZVI slurry. Lab scale proof of concept for CNT air filtration.</td>
<td>Pilot test reported 82 to 96% reduction in TCE. No in situ testing of CNT air filters.</td>
<td>Both use known activated carbon based technology</td>
<td>Chang et al. 2010; EPA 2011e; Ellis 2007; Watlington 2005</td>
</tr>
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</table>
Childhood Obesity

Alleviate food deserts by lengthening storability; Enhance nutrition

Industrial packaging using titanium dioxide as bacteriast disinfectant; Insertion of omega-3 fatty acids into carbohydrates

Formal regulations. FDA approved bulk-TiO2

Nutritional supplements are not drugs: not regulated: informal decisions by individual consumers

Technology risks assessed by food industry: public perception of nano in food, toxicology reports indicate bio-distribution of oral transmission creates acute toxicity in lab mice

Retooling packaging plants to incorporate TiO2 coated cellophane.

Capsulation of omega-3 in carbohydrates.

Unknown energy and materials costs

E. coli, Salmonella, Typhimurium, and B. cereus eliminated by TiO2 encased fresh vegetables. Omega-3 fatty acids enhance nutritional content of carbohydrates.

E. coli killed at 95.67%, 94.27% and 91.61% in 3.0, 5.0 and 7.0 pH solutions in combination with ultra-violet rays.

Limited data on efficacy of omega-3 uptake.

Products are assigned expiration dates based on historical food safety issues (i.e. recalls) and product testing.

Nutrition information based on historical tests.

Wang et al. 2007; Wang et al. 2004; Mihee et al. 2007; Kuzma and Verhage 2006; Siegrist 2007
Lack of renewable energy sources and energy efficiency.

Create utility scale and decentralized photovoltaic arrays. Retrofit homes and businesses with nano-enhanced lighting.

Semi-conductors converting light to energy in CdTe based thin-film LEDs provide high quality light with low energy demand.

Utility regulators, utility operators, electricity distributors, consumers, financiers, and building inspectors.

Regulatory mandates for utilities and market based decisions.

Home and business owners that see energy efficiency retrofits as valuable. Cost parity with fossil fuels, technical feasibility, inconsistent subsidies, current reliability, return on investment of retrofits, efficiency subsidies.

Productio n, material costs, financing, political will, additional storage capacity, and net energy are not all known. Currently 7.3 to 10.2 efficiency is reported for thin-film photovoltaic. Price point is two times existing sources. LEDs provides high quality lumens with reduced energy.

Constraints based on current US grid. Proven efficacy in product testing and measurable outcomes in residential buildings pending.

Regulated utilities must attain renewable energy standards set at 15% by 2024. Meet Phoenix electrical codes.

4.2.4. Addressing the lack of renewable energy supply. Cadmium-telluride photovoltaic (CdTePV) in printed thin-film applications would intervene at the point of power generation and nano-enhanced LEDs at the point of use. The life cycle impacts of CdTePV are 90–300 times less than coal-fired power plant impacts per watt of capacity (Fthenakis et al., 2008). The greatest benefits from CdTePV are realized in the power generation phase, where almost no emissions occur. The Cree Corporation in North Carolina produces nano-enhanced LEDs having long since invested in optimizing the production of 6H-SiC crystals (Edmond et al., 1993). No data are available for a life cycle analysis, as corporate secrets protect the crystal formation processes. Lighting retrofits are the lowest cost, highest return energy efficiency investment, and the most preferred by businesses engaged with the initiative ‘‘Energize Phoenix’’ (Dalrymple & Bryck, 2011). Grid-scale solar electricity and energy storage at Solana Generating Station, currently under construction, will produce 280 megawatts. Solana relies on large-scale batteries that offer 4–6 h of storage (Mahrer, 2011). Positive outcomes abound from these interventions.

However, there are unaddressed issues with both CdTePV and LEDs. The reliability and storability of CdTePV-generated energy may not meet user demands for constant uninterrupted power supply. Storing CdTePV-generated power in large-scale batteries (offering near 100 % reliability) is currently not cost effective (Mahrer, 2011). The plan by Arizona Power Supply (APS) for distribution reinforces preferences for utility-scale solar, rather than addressing uncertainties that accompany rooftop solar. Costs to retrofit the electrical grid from a centralized to a decentralized model will be
significant. Both the societal expectations for electricity and shortfalls in component technologies influence the adoption of these promising (yet unrealized) nanotechnology interventions. A deeper root cause of the problem constellation is the continued growth in the demand for inexpensive electricity to power our expected lifestyles, from entertainment to manufacturing capacity. This and other background drivers remain unaddressed in the proposed interventions.

More profound strategies to address the outlined lack of renewable energy problem require suites of interventions, including non-technical (institutional) interventions such as demand-side management. Recently, the “Energize Phoenix” grant was awarded to assist residents and businesses increase energy efficiency and support renewable energy provision in the Gateway Corridor (a subset of the Energize Phoenix Corridor). The grant exemplifies a partnership between city, businesses, and researchers. Initiated in 2010, seventeen commercial projects were completed in the first year with sixteen of the seventeen total projects were lighting retrofits for an estimated savings of 1.9 million kilowatt hours (kWh) across all the projects (Dalrymple & Bryck, 2011). While businesses have leveraged subsidies and the commercial programs were launched before the residential programs, no residents participated in the first year; all completed energy efficiency projects occurred at commercial properties. A lack of awareness and education, issues of trust, language, and cultural barriers are some root causes preventing homeowners from taking action. The issues of trust range from distrust in the idea of a “free lunch” to distrust of authority and fear of potential immigration enforcement action. Second, limited financial resources prevent residents from paying the $99 fee
upfront for a subsidized energy assessment even though they are rebated the fee later. And, despite a grant to cover 60% of the upgrade costs and a subsidized loan to cover the remaining 40%, residents are hesitant to take on any debt on a property that may have limited or negative equity due to the real estate market, even as the savings in their utility bills are estimated to more than cover loan payments (Dalrymple & Bryck, 2011). In the second year, overall participation in the residential programs increased to approximately 400 households, attributable to increased marketing awareness, outreach to and engagement with trusted community leaders and organizations, exposure to the participation of neighbors, door-to-door community surveying, and community events. However, participation by low-income residents and in the Gateway Corridor continues to lag considerably. This uneven participation response demonstrates that these complex problem constellations are challenging beyond technical feasibility, demanding coordinated efforts to affect change toward sustainability.

5. Discussion

Our study has explored the potential of nanotechnology solutions as a means to mitigating urban sustainability problems. In two cases (contaminated water and energy systems), there is evidence that nanotechnologies can address existing problems. In the case of childhood obesity, the proposed interventions (food additives and food packaging) seem inappropriate in the face of the significant social drivers underlying childhood obesity, as well as the strong apprehension consumers hold against food additives. In all cases, the nanotechnology interventions fail to address root causes, such as demand for electricity, reactive policies addressing environmental contamination, and
consumption of cheap convenience foods and sedentary indoor entertainment.

We are, however, focusing on intervention points and potential effectiveness. Admittedly, these are not technical feasibility assessments and this analysis is not fully inclusive of all decision-making, legal, and economic barriers that comprise robust intervention research. We are taking a broader sustainability perspective on the urban problems to understand just how nanotechnology might intervene and what problem components accompanying initiatives would need to address.

Here, we briefly discuss in how far this study provides insights into the four research questions posed at the beginning. First, over-simplified ideas about sustainability perpetuate the false image that nanotechnology will mitigate the majority of the pressing and complex challenges societies face around the world. It reproduces the technocratic proposition that dominates the progress narratives in industrialized and post-industrial societies (Pitkin, 2001). Clearly, there are nanotechnologies that can intervene in urban sustainability problems, but we ought to be careful not to over-sell their problem-solving potential and capacity. Not all urban sustainability problems are amenable to nanotechnology interventions; in fact, most of them require a suite of interventions, of which technology in general and nanotechnology specifically provide but one stream of solutions. Informed by intervention research, we have argued in this study that a comprehensive problem understanding must inform the appraisal of this potential (Sarewitz & Nelson, 2008).

Second, urban nanotechnological interventions are, at best, midstream interventions, but many are end-of-pipe (downstream) interventions. Systemic
interventions that affect positive changes, especially through upstream interventions impacting key drivers and underlying social phenomena, are critical to long-term sustainable solutions (Midgley, 2006; Schensul, 2009). Social interventions might have significantly higher success rates than technical ones as they offer interventions that address the root causes of problem constellations. Addressing societal demand for cheap convenience foods, the lack of precautionary regulations managing chemicals, or the externalities from fossil fuels not priced into the current power supply—all these issues offer institutional interventions that demand attention on par with technological interventions.

Third, nanotechnology is an enabling technology (on top of other technologies) or a platform (below other technologies) to deliver complimentary technologies. The promised benefits are largely dependent on the distribution and breakthrough of parallel technologies. The unintended consequences that might result from the ‘‘hosting’’ technology as much as from the applied nanotechnology need to be explored through laboratory experimentation, small-scale pilot tests, and research. Nanotechnology will soon play a role in reducing the material requirement for precious metals in exhausts and increase profits in the automobile industry and thereby optimizing an ultimately flawed technology (SDC, 2012). In addition to the traditional environmental, health, and safety concerns, research needs to anticipate the ethical, legal, and social implications, for instance, of pumping high volumes of nZVI slurry into groundwater contaminated with various toxins.

Fourth, there is evidence that LED lighting retrofits and photovoltaic panels will
increasingly be introduced and incentivized. Industrial-scale production of TiO2 awaits the anticipated demand for nanotechnology packaging. Field tests conducted with nZVI slurry show initially promising results to catalyze organic groundwater contaminants. Installing CNT-based air filters into homes and encapsulating nutritional supplements are still held within laboratory-scale experiments. We would argue, however, that these interventions do not address root causes (at all) and only in the energy production and efficiency intervention do they address causing behaviors. The other cases demonstrate the technological path dependencies and the conventional approach of optimization, not disruption and transformational change necessary for achieving sustainability.

6. Conclusion

Clearly, there is potential for nanotechnology to contribute to a sustainable future, but those interventions must be coupled with and embedded in systemic intervention strategies, which are not solely reliant on nanotechnology as the silver bullet. The goal of the presented research is to support initiatives of anticipatory governance that integrate nanotechnology in comprehensive mitigation strategies to urban sustainability challenges that warrant approval by experts and stakeholders alike. Further research on how nanotechnology can be joined with other solution options to comprehensively address urban sustainability problems is necessary. There remains significant work to take a broader scan of all the potential interventions, assess potential pathways, and implement comprehensive strategies to transition these urban sustainability problems into a sustainable future.
Chapter 6

Conclusion

The dissertation builds upon the frameworks of sustainability science and anticipatory governance and shows that they are complimentary. Further it uses these frameworks can be operationalized to analyze technological innovation, assess normative values guiding actors’ responsibilities, construct future scenarios and explore their implications and appraise the amenability of urban sustainability problems to nanotechnology solutions. The dissertation’s chapters address the question: How can nanotechnology be innovated and governed in responsible ways and with sustainable outcomes?

Chapter 2 asked how is nanotechnology currently innovated and governed in the urban environment? Findings illustrate that the city is a powerful organizing mechanism for nanotechnology innovation and governance. The case study on metropolitan Phoenix finds that the dominant actor groups are academic research institutes, industry, and government funding agencies (triple helix). The stakeholder network is divided along product-based sectors with few cross-sector linkages. Considerable governmental support for entrepreneurs (i.e. small business innovation research grants) and academic research via the National Nanotechnology Initiative is enabling the early phases of nanotechnology innovation. All the while, market failures (i.e. the high cost of manufactured nano-products) and corporate barriers (i.e. sunk capital in systematized production lines) are constraining the value proposition of nanotechnology in later phases. The clear objective is to achieve economic returns through the

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commercialization of profitable nanotechnologies and, to a lesser extent, to operationalize (military) nanotechnology as a means to achieve national defense. There is variety and novelty in the types of nanotechnologies created, from solar technologies to personalized medicine; yet little in the way of evidence can be found that nanotechnology in Phoenix offers novelty in the innovation and governance processes. The lack of cross-sector linkages limits opportunities for collaboration, coordination and joint learning. Actors, activities, as well as constraining and enabling factors, follow market-based and closed-collaboration (military) innovation models with little attention paid to the adverse effects, co-construction, or broader public value generation.

Chapter 3 queries how well the current governance and innovation regime performs against principles of risk, sustainability and anticipatory governance (responsible innovation). The study draws upon the descriptive-analytical results from Chapter 2 and assesses the governance regime that shapes nanotechnology innovation against two normative frameworks, the triple-bottom line of sustainability and, the synthesized set of normative responsibilities. Yet, before the assessment could be conducted, a set of bridges was built across the knowledge domains of risk governance, sustainability-oriented governance and anticipatory governance and offers a constructive governance tool for responsible innovation. The stakeholder network pays little attention to those who regulate risks, address liability, communicate science and technology findings, and advocate for citizens. Nanotechnology innovation may offer benefits to those that can afford it, a privileged few. Yet, city officials, citizens, and NGOs are unlikely to participate in the development of the nano-enhanced city. Empirical data
shows that market-oriented values guide stakeholder’s responsibilities 86.0% of the time. The stakeholder network infrequently considers responsibilities that align with societally-oriented and socio-ecological values, 8.5% and 5.5% respectfully. The values underlying nanotechnology innovation are out of balanced when compared to the triple bottom line concept of sustainability. This led to the conclusion that actors are myopically focused on realizing commercial value and, thereby, do not account for the negative consequences that impact society and the environment, today and into the future. Further, there is a complete absence of thought about precautionary policies, labeling mandates, and worker training programs that enhance livelihood opportunities in diverse socio-demographic populations. The most predominant normative responsibility expressed was an assertion that it is the government funding and support agency’s responsibility to shift the science policy agenda toward responsible innovation and sustainability. However, it is broadly understood that government funding and support agencies are responding to mandates expressed by the collective of voting citizens and their representatives in the executive and legislative branches of government. Surely, there is a collective responsibility for setting the science policy agenda that cannot be held, singularly, by government funding and supporting agencies.

Chapter 4 considers what could be the future implications of a continuation of the current innovation and governance regime and how might they contrast with alternative models? This study draws upon the earlier work that analyzes the current innovation and governance of nanotechnology (Chapter 2) and the assessment of that regime (Chapter 3). The study positions the mode of problem solving (innovation model) at the center of
conceptual framework and connects nanotechnology applications, their implications for urban sustainability challenges and the influence and feedback from the broader societal context. Results suggest two nanotechnology innovation and governance models (market-oriented and closed-collaboration) might amplify the lack of social cohesion, livelihood opportunities, as well as resource depletion and large-scale contamination. In the scenario titled, “Will the sun rise? society is further divided along people’s socio-economic status and means. While, in “Controlled and securitized” social tensions and outburst of violence are mitigated with even greater dominance, surveillance, and other control mechanisms (employing suitable nanotechnologies). In contrast, we explore governance models with high levels of public participation or open-source activities that could create a new ‘triple helix’ of innovation, linking public agencies, risk mitigating actors, and civic society. Society might develop a unique practice of collectively addressing urban sustainability problems. This could lead to transformative solutions, including particular types of nanotechnologies that alleviate stresses on people, the economy, and the environment.

Chapter 5 contemplates what are necessary changes to innovate and govern nanotechnology in responsible ways? The study appraises the supply of nanotechnology solutions with the demands of urban sustainability problems. The research conceptualizes urban sustainability problems as complex systems of casually linked elements (i.e. social norms, beliefs and habits; natural and human resources; formal and informal institutions; actions and behavior enabled by technology; negative outcomes; and perceived benefits). It explores just how nanotechnology applications could
technologically intervene into three case studies (i.e. energy use, water contamination and childhood obesity). Results indicate that nanotechnology-based interventions into the selected cases of water contamination, energy use, and childhood obesity, do not effectively address the root causes of urban sustainability challenges. More comprehensive transition strategies are required to complement technological solutions.

The four substantive chapters of the dissertation illustrate that nanotechnology is currently innovated and governed with the goal of commercialization guiding the process. The assessment of that process reveals that the collective responsibilities that guide that process are measurably skewed toward market-oriented values and little attention is paid to values shared by risk, sustainability, and anticipatory governance. A future perspective is taken, while exploring how we might innovate differently and two alternative models (social entrepreneurship and open source innovation) demonstrate that urban sustainability challenges can be addressed through collaborative societal and technological innovation and governance. Chapter 5 reinforces the finding that societal and technological interventions are required, if society wants to comprehensively address urban sustainability challenges. All told, the dissertation shows that anticipatory governance and sustainability science are a means to guiding nanotechnology innovation toward responsible innovation, while reaping the rewards of creativity and knowledge generation at the same as safeguarding against negative consequences.

The findings and outcomes of this research are, largely, not unique to nanotechnology and draw from, and in turn offer broader contributions to the study of technology in society. The dissertation’s findings demonstrate that not only are
nanotechnological artifacts inextricably linked socio-technical changes, but also both are highly influenced by the model of innovation governance. For example, closed collaboration will bring nanotechnology to bear on sustainability challenges, but it will do so in a particular way that excludes certain stakeholders and results in negative unintended consequences. Alternatively, social entrepreneurship is inclusive to more stakeholders and addresses sustainability challenges through coupled societal and technological innovations, which result in fewer negative unintended consequences. Therefore, the governance and conceptual structure of the innovation process itself is central to the outcomes and feedbacks between the resulting nanotechnological artifacts and society.

This research identified disconnects in the social network of nanotechnology in Phoenix and then worked to bring those disparate actors together in new ways, in an attempt to create new linkages. This research has, to-date, not had policy impact, but changes in organizations (information sharing between various network organizations) has created openings for new collaborations. Yet, significant work remains to evaluate the impact of this research and other research projects initiated by the Center for Nanotechnology in Society at Arizona State University (CNS-ASU). Furthermore, the community engagement wrought through the relationship building of fellow members of the Transition Lab in the School of Sustainability (SOS-ASU) positions this dissertation research to engage with people in meaningful ways. That work will be left for those focusing on evaluating the efficacy of the broader center – this dissertation is merely a small sub-component of larger stakeholder interactions and capacity building in the city.
of Phoenix and beyond.

And while this dissertation reflects a significant body of research, limitations abound. One inherent limitation is the dependence on a single case study site. This makes results difficult to translate across time and space. To overcome that limitation, the studies on nanotechnology innovation were designed to, in part, mirror previous studies. Selected elements of this research project are directly comparable to nanotechnology innovation in different socio-cultural contexts.

Conducting additional research in complementary urban regions within the United States and abroad could strengthen the initial findings in this dissertation. Others may pursue research in different urban innovation clusters with comparable characteristics to Phoenix to generate cross-case analysis. The urban study area would, like Phoenix, need to be a state’s capital, be a late entrant in nanotechnology innovation, and have similar environmental and social justice challenges – a number of cities (e.g. Atlanta and Minneapolis) offer promise. This would take the initial research findings, currently bound within a given socio-cultural setting, and broaden the impact.

Specifically, the normative responsibilities offered in chapter 3 have only been tested against one case study, at this point. The normative responsibilities are not (in and of themself) a strategy to achieve responsible innovation. They offer a tool to people seeking to pursue nanotechnology innovation with the concepts of risk management, sustainability and anticipatory governance in mind. Additionally, actors’ perceptions of responsibilities are grouped (self and other assigned) in this dissertation’s analysis. Separate analysis that parses the differences remains to be completed.
Some of these limitations are due in part to my commitment to operate as an engaged sustainability scientist in conducting this research. In this mode of research I actively engaged with local community members, with various networks of specialized practitioners, as well as with nanoscale scientists and engineers. Traditional scientific practice focuses on uncertainty and methodological issues within a clearly defined disciplinary boundary. Alternatively, my research explored problems that were co-defined with citizens and stakeholders, relying in part upon their experiential knowledge. After the problems were co-defined, I repeatedly engaged with a cadre of stakeholders in city administrations and non-governmental organizations, in private investment firms and start-up entrepreneurs, in high schools are academic research institutions. Those engagements were all in an effort to combine societal discourse and scientific discourse as a means to co-create knowledge that is transferable to solution-based initiatives. These two steps (i.e. co-defining the problem and co-creating knowledge for solution initiatives) attempted to align with two phases of the ‘ideal-typical transdisciplinary process’ detailed by Lang, Wiek et al. (2012). However, challenges arose during my research and my research is far from the ‘ideal-typical transdisciplinary process’. Nor does it move into the third phase, ‘re-integration and application of created knowledge’ (Lang, Wiek et al., 2012). A number of barriers presented themselves early on the research.

The first immediate and pressing barrier was a knowledge deficit on my part, since prior to starting this research I had not studied nanotechnology at all. Secondly, the language barriers presented by the specialized disciplinary and stakeholder groups needed to be overcome for meaningful scholarship to begin. Thirdly, I had to build trusted
relationships with key stakeholders, which ultimately presented windows of opportunity for frequent and recurrent engagement with people in the Phoenix community.

The work and effort to overcome these challenges paid off in a number of ways. Through the engagement activities, I gained a voice in the process and acted as a convener within the network of stakeholders, which led to opportunities to gain and share knowledge. The collaborative approach and partnerships with stakeholders offered reflection in both directions (between my collaborators and I). Those collaborative partnerships informed the practice and offered feedback to stakeholders involved in nanotechnology innovation leading to moments of knowledge co-construction, such as a moment when the potential dangers and societal implications became clearer. A shared discovery was made regarding wastewater containing nanoparticles that are pumped into the groundwater for long-term storage as part of the city’s future water reserve. The idea that the risk does not just flow ‘downstream’, but is temporarily out of sight and out of mind, yet beneath our very feet, was revealing to me and to my collaborators.

Yet, practicing sustainability science was not without its challenges and I experienced quite as I attempted to operate as an engaged sustainability scientist. I attempted to directly engage people who have a stake in the current and future directions of nanotechnology in Phoenix, yet immediately I was faced with a lack of problem awareness and complacency on the part of many stakeholders. Recruitment and forming collaborative partnerships took countless hours, days, years and some people never responded. My attempts to bring people together into a team were crippled by minimal support from legitimate network leaders. People, even those from my home institution,
openly questioned my methods during workshops and other events. Those questions undermined and delegitimized the process at times. In between engagement activities (i.e. meetings, interviews, workshops, public events, and informal settings) people stopped responding or the responsibility to participate was transferred to another individual. For example, one chief executive officer (CEO) delegated workshop participation to a manager and another CEO delegated participation to an administrative assistant – who took notes at the meeting as a means to report back to their boss. I was forced to enter quickly into stakeholder engagements, at times taking shortcuts and compressing my background literature reviews and planning efforts. Often compressed timeframes between data collection and workshops intended to facilitate extended peer-review led to last minute work plan revisions with unimpressive results.

This work took three years, and yet there might be only a slight increase in the awareness of stakeholders about the societal implications of nanotechnology. There are few methods that can capture for observable changes in practice or policy. At the same time, if I had not performed the academic scholarship that described, analyzed and evaluated an object of study, my degree requirements would have been unfulfilled. This tension between fulfilling degree requirements and engaging in ‘real world’ problems, which I experienced on a small-scale is being played out across academia.

Academic research is being pulled in two very different directions. On the one hand is the long-term perspective of traditional disciplinary academic research and on the other are the critical and urgent ‘real-world’ challenges. The traditional mode of science is to deliver carefully packaged knowledge in the form of papers and presentations to
decision-makers. If the grand challenges facing the planet are truly urgent, the science enterprise needs to go beyond describing, analyzing and evaluating scientific problems. There is a need for academic researchers to address societal challenges and contribute to solutions, despite the inherent uncertainty. This makes a strong case for a new form of science that can overcome the traditional science-society boundary and can act pragmatically in the face of uncertainty. Sustainability science offers a new space for academic research to be more transboundary and to take pragmatic decisions in the face of uncertainty. This transboundary work requires a high level of engagement with stakeholders in the co-definition of the problems, in the interpretation and peer-review of results, and in the formulation of solution-options (c.f. design principles in Lang, Wiek, et al., 2012).

This leads to another tension, the path forward for this work. Significant work remains to craft and test strategies that can constructively guide social and nanotechnological innovation in order to harvest the positive potential of nanotechnology and safeguard against its negative consequences. There are thirty-three normative responsibilities offered in chapter 3 of this dissertation that can be consider as potential intervention points into the current nanotechnology innovation process and used in experiments. By bringing together a network of like-minded scholars these responsibilities could be used in social experiments in different places around the world and in Phoenix, alike. The scenarios presented in chapter 4 need to be brought back into deliberative stakeholder forums. Hopefully the scenario’s depiction of the future implications of nanotechnology in the city can spark constructive debate. Yet, those
debates are still not enough. There is a pressing need to identify actionable steps that can be tested and assembled into a comprehensive strategy that leverages a conceptual understanding of nanotechnology innovation and governance.

Aside from the academic contributions, this dissertation offers practical and tangible knowledge to city, county, state and federal agencies, who all influence nanotechnology innovation, specifically, and science, technology and innovation, more generally. This dissertation demonstrates how a scholar can practice research within an academic research institution, such as ASU, attempting to be socially embedded and cognizant of challenges in their surrounding community.

If city leaders in economic development want jobs, any jobs, then they have started to relinquish control over the future directions their city. The businesses that join a city will have lasting impacts, even if the companies do not last. Consider who is being rewarded with land easements, infrastructure investments, and tax breaks offered by city economic development offices. Craft guidance documents and be strategic in your recruitment efforts to target the ‘right’ companies for your city. A vision for your city and the political will to act strategically should help you navigate toward that vision, take greater care in the attraction, retention and local development of business ventures. Look to support local entrepreneurial efforts that creatively solving problems the city is facing. Partner with other city governments, state and federal agencies to address challenges that are more widespread and cut across political boundaries.

West of the Mississippi, county leaders, in addition to state governments are responsible for balancing their time and resources between urban and rural communities
and that is understandable. Yet, almost all high-tech patenting and publication activity, specifically in nanotechnology, is occurring in urban regions. Take an active role in funding science, technology and innovation through seed grants and ‘start up’ competitions that incentivize entrepreneurs who offer solutions to the pressing challenge facing your region, don’t just reward technological and economic merits. The Arizona Commerce Authority could do just that in their next round of entrepreneurial grants. Consider the multiplicative effects of supporting creative problem solvers and incentivizing them to address problems that are currently too costly or otherwise seem infeasible. State governments that partner with city leaders will realize lasting positive benefits by being strategic in their science, technology and innovation investments, and in recruitment and retention efforts.

The federal government, even more so than cities and states, has hundreds of levers to push and pull to affect science, technology and innovation. Three clearly stand out:

1. The federal standards for K-12 education need to support critical thinking and problem-solving skills, opposed to routinized memorization.

2. The efforts made, in terms of national security from science, technology and innovation need to be translated into mission-oriented agencies committed to addressing urban sustainability challenges and structured with the same long-term planning commitment.

3. Federal agencies need to help coordinate information sharing and make knowledge actionable between federal, state and urban regions at different
scales.

Combined, talented populous and mission-oriented agencies focused on sustainability problems, and coordination across governmental scales is a promising combination.

Academic institutions from business schools to technology institutes can also takeaway lessons from this dissertation. Business schools can take the thirty-three normative responsibilities offered in the comprehensive framework and apply them to case study research. Hundreds of case studies, student projects and thesis are needed to test the effectiveness of these tenets to affect positive outcomes. On the other side of campus, in the offices of technology transfer there are opportunities to go beyond licensing new technologies to build non-enrollment revenues. Technology transfer offices can look for inventions, which might not garner high licensing fees, but will make positive impacts in local, regional or global communities. License those technologies with socio-ecological goals in mind, rather than holding out for the highest economic return.

The business community, a diverse group of organizations can utilize two key points. First, consultants and insurers performing technology assessments and liability analysis can use the normative responsibilities to evaluate how decisions will led to ‘upstream’ and ‘downstream’ impacts. This will enhance their, respective, appraisals. Secondly, corporate officers and research and development managers can find ways to integrate the responsibilities into the design process and, thereby, affect positive outcomes, enter new markets and minimize material and energy costs in future product manufacturing.
Further, there is a need for a new type of venture capital firm. New venture capital firms need to combine the mandates of a non-profit foundation, like the BRAC Organization and the cunning recognition of value like the Berkshire Hathaway Group. The firm’s goals, however, would aspire to targeted interventions coupled with social interventions and support that support a community’s desire to change. An investor is needed that understands the cultural context, partners with community organizations and then partners with appropriate stakeholders to develop comprehensive strategies.

And last, but certainly, not least, residents and citizen advocates need to organize to address place-based challenges central to their community. There is plenty of room to operate and make their voices heard. Advocacy organizations need to connect with economic development agencies at the city, state and county level to communicate what types of businesses they want in their community. They can advocate for small business investments and investments in the entrepreneurial capacity within their community.

Significant resources are being spent on bringing in large corporations from outside Phoenix and very little is being directed to community-level entrepreneurial efforts. In Phoenix and across the nation, a lack of investments in public education is a long-term, community-based challenge that will undermine a children’s ability to compete in the global workforce. That issue alone demands shifts in resource allocation and the utmost attention by active community groups and residents.

This research is an early attempt to understand how urban regions are currently organized to generate technological innovation as a means to solve problems and what the implications of those approaches might yield. The dissertation offers knowledge to
academics and practitioners in urban regions, not just metropolitan Phoenix, about how they can organize themselves to foster responsible innovation. The persons and organizations engaged during this research, represent a diversity of decision-making groups that can affect positive changes and address the critical urban sustainability challenges facing their cities. Urban regions have the capacity to address these challenges through both social and technological innovation and the lessons offered here offer a guide towards more sustainable outcomes.
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**Chapter 6**

APPENDIX A
PERMISSION OF COAUTHORS TO PUBLISH WORK IN DISSERTATION
Dr. Arnim Wiek, and Dr. David H. Guston gave permission to publish previously coauthored work in this dissertation.
Office of Research Integrity and Assurance

To: Amin Wake
   GCIS Build

From: Mark Roosa, Chair
       Soc Beh IIR

Date: 05/12/2011

Committee Action: Exemption Granted

IRB Action Date: 05/12/2011

IRB Protocol #: 1100006418

Study Title: Center for Nanotechnology in Society: Thematic Research Cluster-2: Urban Design, Materials, and the Built Environment (or "nano and the city").

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2).

This part of the federal regulations requires that the information be reported by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that it disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.
To: Amim Vais  
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From: Mark Roosa, Chair  
Soc Behl IRB  
Date: 09/21/2012  
Committee Action: Exemption Granted  
IRB Action Date: 09/21/2012  
IRB Protocol #: 1208008255  
Study Title: Scenario Study: Center for Nanotechnology in Society: Thematic Research Cluster-2: Urban Design, Materials, and the Built Environment (or “nano and the city”)  

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Soc Beh IRB

Date: 02/23/2011

Committee Action: Exemption Granted

IRB Action Date: 02/23/2011

IRB Protocol #: 1102006088

Study Title: Center for Nanotechnology in Society: Thematic Research Cluster-2:UrbanDesign, Materials, and the built Environment (or “nano and the city”)

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