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Nanotechnology in the City: Sustainability Challenges and Anticipatory Governance

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ABSTRACT *Visions about the use of nanotechnologies in the city, including in the design and construction of built environments, suggest that these technologies could be critically important for solving urban sustainability problems. We argue that such visions often overlook two critical and interrelated elements. First, conjectures about future nano-enhanced cities tend to rely on flawed concepts of urban sustainability that underestimate the challenges presented by deeply-rooted paradigms of market economics, risk assessment, and the absorption of disruptive technologies. Second, opportunities for stakeholders such as city officials, non-governmental organizations, and citizens to consider the nature and distribution of the potential benefits and adverse effects of nano-enabled urban technologies are rarely triggered sufficiently early. Limitations in early engagement will lead to problems and missed opportunities in the use of nanotechnologies for urban sustainability. In this article, we critically explore ideas about the nano-enhanced city and its promises and limitations related to urban sustainability. On this base, we outline an agenda for engaged research to support anticipatory governance of nanotechnologies in cities.*

KEYWORDS *Nanotechnology; City; Urban Visions; Sustainability; Anticipatory Governance; Sustainability Science*

Visions of the Nano-Enhanced City

Imagine:
Photovoltaic materials cover horizontal and vertical building surfaces. Enhanced by multi-functional nano-scale designs, they capture light and convert it into electric power for buildings and the urban infrastructure. At night, they re-emit visible light for their buildings and surroundings.

With the addition of engineered nanomaterials that change the crystalline structure of concrete, imaginative architectural designs become possible and buildings achieve new heights and forms. Steel reinforcements are a thing of the past as concrete structures have ample strength to support themselves, in shapes that make the Guggenheim Museum look tame. Engineered from the strongest, lightest nanomaterials, suspension bridges and other weight-bearing elements look more like spider webs than structures.

Active nano-coatings of titanium dioxide and other catalysts, which break down soot and grime that settles on surfaces, keep buildings and sidewalks sparkling clean.

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These surfaces also scatter light in a way that eliminates glare, making roads and cycle ways safer during the morning and afternoon rush hours.

The addition of fire retardant nano-particles and coatings into new building materials and household products has changed the way we think about fire. Plastics, carpeting, paint, and wallboard are all fire resistant. With pressure treatments for wood items and nano-fibers integrated into paper, there are few flammable items left in the modern home. Building codes no longer require installing sprinkler systems into buildings if they have incorporated sufficiently fire-resistant material in construction.

Engineered nanomaterials are now widely used in the city. Carbon dioxide and other air pollutants are reduced as power plants, buildings, and vehicles use nanostructured membranes. Recycled water is purified with nano-enabled filtration and osmosis systems, and these systems are available for individual households and new local urban water treatment systems. (This futuristic vignette is grounded in selected nanotechnology studies referenced in the section entitled, "The Ambivalence of Urban Nanotechnologies.")

Such visions of the benefits of nano-scale science and engineering (NSE) exemplify ways in which nanotechnologies are expected to be crucial in solving urban problems through innovative applications in buildings, infrastructure, energy, water, transportation, security, information, and other urban systems. These systems are liable to be influenced by emerging nanotechnologies in ways that will alter the experiences of city dwellers with respect to their housing, mobility, communication, consumption, and other activities.

We define *urban nanotechnologies* as products, structures, and processes using engineered nanomaterials[1] that are embedded in the "urban fabric," that is, the dynamic, spatially-agglomerated complex of activities, buildings, infrastructures, technical devices, ecosystems that comprise the contemporary metropolis. Many proposed urban nanotechnologies are projections of isolated applications, set only marginally in the urban context (e.g., *http://nanoarchitecture.net/*). More sophisticated visions of nanotechnologies in the city that go beyond straight-line extrapolations and technocratic visions to address the complex reality of cities with their particular interwoven social, technical, and ecological components are less common. All these visions of urban nanotechnologies continue a persistent optimism evident in the rhetoric surrounding nanotechnology (Selin, 2007).

Our focus on urban nanotechnologies is derived from an appreciation of the profound, potential consequences of urban nanotechnologies. Yet, while nanoscale science and engineering has attracted massive public funding in recent years (Shapira and Wang, 2010), we are concerned that the interplay of societal impacts and these emerging technologies in the built environment has yet to be fully anticipated. Arguably, the nexus of science and technology with the urban context is weaker in contemporary scholarship and practice than at times in the past. Yet, some recent studies promote a more profound perspective on this nexus, for instance, the link between ICTs and urban development (Aurigi, 2006; Rutherford, 2011). In mid-twentieth-century United States, this nexus was apparent across cultural perspectives from the 1933 Chicago World's Fair to the critical works of Lewis Mumford. Into the 1960s and 1970s, housing policy had connections with technology policy (Nelkin, 1971). Technology transfer−−which now tends to be viewed primarily as the movement of university intellectual property to the commercial sector−−was, prior to the 1980s, seen more broadly as the movement of knowledge created at the federal level to state and local governments. While there is a robust literature on science and technology in regional economic development and a less systematic one on local and indigenous knowledge, there is relatively little place-based consideration of science and technology (Hommels, 2005). Urban planning has, since Mumford's day, moved away from centrally considering science and technology, even while embracing environment and sustainability in recent years (Bugliarello, 2004). Overall, science and technology's peripherality to current urban planning and policy is all the more worrisome given that cities are not only home to the majority of humanity, but are also hubs of the learning, creativity, and innovation that need to be harnessed to develop solutions to problems of urban sustainability (Brand, 2005; Beatley, 2007).

A further argument for reflecting on nanotechnology through the lens of the city builds upon the potential of *participatory* technology governance. The governance of emerging technologies like nanotechnology is increasingly conceptualized as a deliberative process that should involve the broader public as stakeholders and decision makers (Renn and Roco, 2006; Guston, 2008; Brown, 2009). However, recent studies suggest that the broader public has limited knowledge of and, even more important, limited *experiences* with nanotechnology (Satterfield et al., 2009; Cacciatore et al., 2009). These studies have widely used decontextualized (even if specific) nanotechnological applications as stimuli, removed from rich, real-world contexts and, therefore, somewhat intangible to laypeople. In contrast, embedding nanotechnology into a real-world experiential context (contextualization) such as the city facilitates but also enables public deliberation of future technologies, needs, sustainability, risks, and so forth through tangible and familiar environments (Delgado et al., 2011). Such participatory and anticipatory explorations, however, might be more feasible in currently urbanizing cities than in older established cities where resistance might emerge from entrenched urban infrastructure.

The Center for Nanotechnology in Society at Arizona State University (CNS-ASU), in collaboration with partnering institutions from academia, business, government, and civil society, has embarked on an exploration into the nano-enhanced city (Foley and Wiek, 2012; Wiek, Guston, et al., 2012). The guiding approach for this endeavor is a novel combination of anticipatory governance and transformational sustainability science. In this article, we first explore the ambiguous potential of urban nanotechnologies, acknowledging both utopian visions, as above, and dystopian scenarios. The article then explores a set of questions derived from concerns for sustainability and for anticipatory governance raised by emerging technologies in general, and urban nanotechnologies in particular. The article concludes with an outline of the sustainability research program on urban nanotechnologies undertaken by CNS-ASU, which engages a variety of stakeholder groups and integrates knowledge across disciplines, including nano-scale science and engineering itself.

Urban Sustainability Challenges

There is ample evidence that cities worldwide are struggling to cope with a variety of urban challenges (Bugliarello, 2011). As a result of rapid urbanization over the past few decades, the majority of the world's population lives in urban areas, and urbanization processes are projected to continue, especially in low- and middle-income nations in Africa, Asia, and Latin America (Satterthwaite, 2009). The key drivers for urbanization are manifold, ranging from real improvements of living standards through prevalent urban images and clichés to manipulation and exploitation (Gilbert and Gugler, 1992; Kofman, 1998). Despite the social and cultural achievements accumulated in urban areas around the world (Glaeser, 2010), the reality of most cities encompasses a variety of demanding problems and challenges (Evans, 2002; Beall and Fox, 2007; UN-Habitat, 2008). The economic and social gains achieved by population concentration through urbanization are now challenged by adverse effects due to growth in size, complexity, and other features that exceed cities' governance capacities (Pile et al., 1999; Bugliarello, 2011). In high-income nations like the United States, cities face critical challenges such as social segregation, inadequate housing, environmental degradation, poverty, crime, decaying infrastructures, inaccessible public services, and limited public engagement in urban governance (Kim and Gottdiener, 2004). While per capita carbon emissions may be lower in cities than rural areas (Brown et al., 2008), cities in high-income countries are often places of over-consumption, relying non-resiliently on regional to global supply chains of water, oil, raw materials, agricultural products, labor, and so forth (Beatley, 2007; Kennedy et al., 2007). Cities in low- and middle-income countries face comparable challenges, intensified by the pace, scale, and rising complexity of growth (Kim and Gottdiener, 2004; UN-Habitat, 2008).

Each city faces a specific constellation of these problems that it may share with only a small subset of other cities (Bugliarello, 2004). For example, metropolitan Phoenix, which includes more than four million inhabitants and covers 16,500 square miles, shares issues of urban sprawl, traffic congestion, air pollution, social segregation, and obesity with other American metropolitan areas. But it is located in the Sonoran Desert with very sparse rates of precipitation. While water supply and water infrastructure are, therefore, an intense issue, it is getting even more challenging from a sustainability perspective when considering the nexus between water and energy, namely, energy used for water provision and water used for energy production (Perrone et al., 2011). Urban challenges are situated in specific cities with unique or distinctive contextual features that influence the relative success of technological interventions in them.

Sustainability scholars and practitioners attempt to take a holistic perspective on the constellation of urban problems, calling attention to the long-term viability of urban areas and societies (Kates et al., 2001). Not all urban problems are urban *sustainability* problems, that is, threatening the very existence of the city in the long-term. Yet, some of the problems envisioned above, and particularly their mutual reinforcement, are not mere and transitory inconveniences (Ferguson et al., 2007). Recent studies suggest that as societies and ecosystems reach tipping points, large-scale collapse as an outcome cannot be discounted a priori (UN Habitat, 2008; Rockström et al., 2009).

Expanding disciplinary or sectoral approaches to environmental degradation, economic decline, or lack of social cohesion, our perspective of urban sustainability requires linking these adverse phenomena, evaluating their harmfulness and urgency, and tracing them back to their root causes (Ostrom, 2007; Wiek, Ness, et al., 2012). Simply allocating the described problems to cities obscures probing of root causes. As Satterthwaite (2008: 539) states: "[It] would be misleading to attribute [greenhouse gas emissions] to 'cities' in general, [for] they should be ascribed to the individuals and institutions whose consumption generates them." And consumers are closely linked to actors who extract materials, produce, distribute, and sell goods, offer services, and dispose of waste. The focus on people and their interactions, needs, motives, and norms allows the negotiation of responsibility and accountability, and is thus a prerequisite for making real progress in *solving* sustainability problems. There is a rich set of urban technologies and an array of institutional frameworks that mediate and influence this complex chain of causes and effects.

Cities are hubs of urban technologies, and urban life is closely linked to technologies perceived to produce individual or collective benefits. But urban technologies are also structural factors in urban (sustainability) problems, which channel individual choice and action along certain trajectories (Bugliarello, 2004; Brand, 2005). Car-dependent infrastructure, non-renewable energy technologies, asbestos-containing construction material, and guns are just a few illustrations of the ambivalent character of technologies that are built into our cities and shape the contours of our lives within them. Underpinning the deployment of urban technologies are institutional frameworks of governance and market operations that influence design and use, including through pricing, accessibility, and regulation (Bugliarello, 2011). These frameworks also differ across cities and countries, for example in planning for green belts, the provision of mass transit, or the privatization of water and utility services.

Another layer of complexity is added when considering that technologies are widely regarded and promoted as *the* means to solve urban problems. From catalytic converter to waste water technologies, solar technology, and security systems, there are a great number of technical solutions proposed to address urban challenges (Coates, 2001; Beatley, 2007). Yet, path dependency, rebound effects, and unintended consequences are some of the concerns held up against "technological fixes" (Perrow, 1984; Hällström, 2008; Sarewitz and Nelson, 2008). The sustainability discourse emphasizes the importance of reflecting on the challenges we face from a broader societal perspective that goes beyond technical solutions and deliberating on what we "need," what we are willing to risk, and what we envision our heritage to be (Leiserowitz et al., 2006).

The Ambivalence of Urban Nanotechnologies

Numerous scientific studies emphasize the potential contributions of urban nanotechnologies to sustainability and sustainable development (Salamanca-Buentello et al., 2005; El-Samny, 2008; Andersen and Geiker, 2009; Bittnar et al., 2009; Rana et al., 2009; Saxl, 2010; Smith and Granqvist, 2011). These visions are diverse, covering many specific urban domains from construction through energy and water supply to transportation. Each particular application is argued to provide benefits−−some of them outlined in the introductory futuristic vignettes above. Other examples of applications are: nanomaterials enable construction that is more resilient to stress and returns less heat to the environment, thus mitigating the urban heat-island effect (Gopalakrishnan et al., 2011); nano-coatings for glass and other building surfaces reduce the need for cleaning, thus saving water and cleaning liquids based on petro-chemicals (Bittnar et al., 2009); nano-photovoltaics provide solar energy without large-scale transmission, thus reducing greenhouse gas emissions (Kanamura et al., 2010); nano-enhanced airbag accelerometers in cars protect passengers from being injured in crashes, thus reducing the carnage on roadways and the burden on emergency responders and hospitals (Mamalis, 2007); nano-based photocatalytic applications eliminate pollutants from drinking water systems (Li et al., 2008) or from the air along roadways (Pacheco-Torgal and Jalali, 2011), thus reducing adverse health effects; self-healing synthetic systems that sense damage and mend defects, thus, reducing material intensity and saving resources (Mauldin and Kessler, 2010); and smart, multi-functional devices performing several of these tasks simultaneously, thus multiplying benefits (Smith and Granqvist, 2011). For all of these applications, the referenced studies present, at least, initial empirical evidence that the envisioned benefits can get realized.

Advocates of the use of nanotechnologies in the city naturally highlight the expected positive contributions that will result from their deployment. Yet, the benefits of urban nanotechnologies are unlikely to be evenly distributed, and there may well be negative implications. Imagine the following extensions of the introductory future scenes:

A gated community, mainly inhabited by middle-class retirees, is bordered by neighborhoods that are populated mostly by working poor and recent in-migrants. Favorable tax breaks in outlying suburbs have prompted large businesses to abandon the neighborhoods or outsource the majority of their higher-paying jobs. Many smaller businesses have closed too. Unemployment in these neighborhoods is far above the city average. Rising crime is a concern. There are now few local opportunities for employment, although some neighborhood residents do find work in the nearby gated community. Domestic laborers for the yards and homes in the gated community now submit to biometric security measures for access to their workplaces, and there are plans to introduce on-body sensors to assure that laborers go only where they are supposed to within the gates.

In the city's low-income neighborhoods, the high school graduation rate has dropped to less than 20 percent. Budget cuts have eroded the educational infrastructure and led to the closing of libraries and community centers. The lack of educational opportunities and the social and intellectual capital that they generate means poor outcomes and increasing "gaps" in other areas, including health and jobs. Nano-enabled personal health-care diagnostic devices are now on the market. These devices are available for under $1,000. However, those with less education and, particularly, those without jobs that provide health care, do not use them. Local free clinics in the neighborhoods do use some of these devices, but find that many of their patients are unable to afford follow-up services.

In several locations across the city, the latest nano-enabled testing devices show that air, water, and even soil are contaminated with nanoparticles produced in industrial settings and eroded from the various coatings, water treatments, and other applications. Community advocacy groups attempt to make the challenging scientific case for chronic, low-level adverse impacts on human health and the environment. They also argue that some locales are used as "nano-dumps," filled with unlabeled nano-enhanced products and materials that have toxic potential but are insufficiently regulated under the current regime. Un- and under-employed adults and even children scour these dumps for the precious metals used in the discarded nano-devices, exposing themselves to higher levels of risk and accounting for several acute cases of nano-toxic effects.

The built environment, particularly the housing stock, is of poor quality, energy supply continues to be based on non-renewable sources, and actual energy use is highly inefficient due to old appliances, a lack of awareness of alternatives, and competing priorities——even while more efficient alternatives are financially attainable. Landlords who do make improvements often spray nano-coatings onto windows and other surfaces to make buildings as a whole more efficient, but neglect individual units. Many neighborhoods have attempted to compete, unsuccessfully, for basic infrastructure that would support walking and biking, so local air quality remains poor and neighborhood streets remain dirty and *dangerous places for pedestrians, children and visitors.* (This scenario vignette makes implicit reference to the urban sustainability studies referenced in the previous section and uses some of the patterns of ambivalence outlined below in this section.)

This scenario is a plausible complement and contrast to the earlier futuristic vignette and reinforces the point that a variety of societal, economic, and environmental impacts are likely to be associated with urban nanotechnology applications. As the wave of promising nanotechnological innovations is starting to reverberate in cities around the world, it seems timely to reflect critically on the potential of these technologies to mitigate or solve urban sustainability problems (Wiek, Foley, et al., 2012). This requires embedding and deconstructing the prevalent NSE visions of urban nanotechnologies within the complex reality of cities. We share the position articulated by Sarewitz and Nelson (2008: 871): "Not all problems will yield to technology. Deciding which will and which won't should be central to setting innovation policy." It is apparent that urban nanotechnologies have the potential to address multiple urban challenges, but it is vital to probe how and with what effects and whether there are more sustainable alternatives. Questions that need to be addressed include:

- What urban sustainability problems are nanotechnologies capable of mitigating or solving (now and in the future) and are these challenges the most pressing and salient ones from a sustainability perspective?
- What will be the costs (in a comprehensive sense) of such nanotechnological fixes? Who will benefit from the fixes and who will bear the costs? Do the promised benefits justify the associated costs?
- Are there alternative solutions (including non-technological ones) that could yield results more quickly, more effectively, more efficiently, and with fewer (harmful) side effects?
- Are expected costs, benefits, and alternative solutions adequately deliberated and balanced in the current governance regime (and if not, what changes are needed)? For instance, do current funding schemes and R&D priorities for nanotechnology adequately account for their potential, or lack thereof, to mitigate (urban) sustainability problems?

We recognize that these questions are not always easy to answer due to a combination of entrenched operational paradigms. At least four major areas of ambivalence and contestation can be identified: (1) market and governmental failure; (2) the risk paradigm failure; (3) disruptive technologies failure; and (4) social amplification of risk.

Market and Governmental Failure

Nations pursuing major initiatives in nanotechnology are doing so largely for reasons of economic competitiveness and techno-nationalism. While these are legitimate state goals, it is also clear that economically successful technologies are not always socially and environmentally optimal. The market aggregates preferences in large part by the ability to pay, and new technologies are, therefore, often designed to cater to relatively well-off early adopters. Government sponsors public R&D, but its priorities reflect the interests of universities and existing industrial incumbents. It is, therefore, crucial to start with the framing of net benefits associated with urban nanotechnologies: Who are the intended beneficiaries of, and what is the market for, urban nanotechnologies? Who can afford to use these applications and who would profit from their large-scale dissemination? Does the adoption of nano-enhanced urban technologies either reinforce existing economic inequities or help redress them? What governance changes are necessary to ensure sustainable outcomes from economic, societal, and environmental long-term perspectives? Critical Science and Technology Studies reveal a history of technological innovation that has seen a great deal of "progress" without tackling underlying issues of sustainability, including equitable distribution. A great deal of technological innovation is driven by the paradigm of economic growth, simply *replacing* functioning technologies or social practices (Higgs et al., 2000; Hornborg, 2001; Feenberg, 2002).

An exemplary case of the market paradigm and associated governmental failure can be seen in the relationship between nanotechnologies and human development goals. In 2000, the United Nations articulated its *Millennium Development Goals* to set clear and achievable targets for progress in human development worldwide. The UN report cited nanotechnologies as potentially important contributors to achieving the goals. Despite the acknowledged potential (Barker et al., 2009; Liao, 2009), there remain questions about the actual role of nanotechnologies in achieving these goals, especially considering significant social and political hurdles (Invernizzi and Foladori, 2005; Maclurcan, 2005; Salamanca-Buentello et al., 2005; Schummer, 2006), and of whether the market under current paradigms is capable of delivering nanotechnologies for low-income communities. Preliminary assessments suggest how nanotechnologies as currently developed and deployed may not be up to facing challenges of equity, equality, and development (Cozzens and Wetmore, 2010).

The Risk Paradigm Failure

Over the last years, the NSE community and governments funding NSE research have emphasized efforts to understand the environmental, health, and safety (EHS) risks of engineered nanomaterials (Hansen et al., 2008; Warheit et al., 2008). While such issues were patent from the beginning, it took some time for EHS research to begin—not only because of a general enthusiasm for the benefits of nanotechnologies but also because of the technical and logistical challenges of doing EHS research with new materials that are highly variable and for which few if any standards of production or testing exist.

Toxicological studies suggest that some engineered nanomaterials may pose both environmental and health risks, including asbestos-like pathologies in response to exposure to carbon nanotubes (Fadeel et al., 2007; Kane and Hurt, 2008; Shatkin, 2008; Ray et al., 2009). Although there is dispute and controversy about such findings (see, for example, Monica and Monica, 2008), there is an emerging consensus that the EHS issues associated with nanotechnology need attention. Yet, EHS questions also need to be situated in the urban environment—e.g., is the nano-city the clean and low-emission city of the future, or will new nanomaterials create pollution and waste streams that aggravate urban challenges? The disposal of nano-waste, its long-term environmental behavior, and regulatory approaches to these questions remain an open problem (Breggin and Pendergrass, 2007). Large-scale, nano-enhanced surfaces of urban buildings and infrastructures, for example, are exposed to wind and rain, thus triggering erosion that can lead to air transmission and deposition of nanoparticles in soil and water (Ray et al., 2009). And a recent review of EHS issues of nanomaterials in the construction industry concludes that "beyond the current excitement about the possibilities of MNMs [manufactured nanomaterials] to enhance our infrastructure, there are reasonable concerns about unintended consequences" (Lee et al., 2010: 3586).

While we can formulate risk-related research agendas and risk policies, there are questions about nanotechnologies that are formally "beyond risk." These range from the trans-scientific questions of how to approach the tens of thousands of combinations of relatively simple nanomaterials (e.g., the many different aspect ratios of single, double, and multi-walled carbon nanotubes), to the vexing challenges of understanding how nanotechnologies fit into complex systems, to the utterly unquantifiable questions about emergent hazards at the intersection of nanotechnologies with other novel applications like biotechnology (Dupuy, 2007). Finally, considering the emerging shift towards *active* nanostructures (Subramanian et al., 2010), new dimension of risks need to be considered that challenge current risk assessment paradigms (IRGC, 2008).

One example is the current and growing use of engineered nanomaterials for self-cleaning glass in the urban environment. Such glass, used for example on the roof structure of St Pancras Station in London, is covered by a catalyst such as titanium dioxide (TiO_2) which breaks down dirt particles that can then be washed away when it rains. Self-cleaning glass can reduce the use of water and energy otherwise used in cleaning. On the other hand, there are concerns that the oxidization of organic pollutants into acids generates carbon dioxide (CO_2)—a greenhouse gas that contributes to global warming. These emissions might not be significant, yet a full life-cycle approach would need to account for a broader spectrum of impacts, starting from the environmental and social impacts of titanium mining practices in developing countries and concluding with the environmental consequences of the byproducts of the intended reactions (Garvey and Newell, 2005; Robichaud et al., 2009). An approach is needed that makes the systemic, the complex, and incalculable at least somewhat more tractable.

Disruptive Technologies Failure

Nanotechnology is often characterized as a "disruptive" technology, which will radically transform markets through new products and processes and, in so doing, disrupt existing markets. If that happens to be the case, it of course demonstrates the mendacity of the risk paradigm for confronting such technologies. But even at their most sweeping, disruptive technologies do not wipe history completely away, and the challenges of path dependencies and "end-of-pipe" technologies remain.

Ironically, the majority of nanotechnology applications are *not* disruptive. They offer incremental changes to existing urban buildings and infrastructures, e.g., coatings or additives, rather than radical shifts to new ones (Wiek, Foley, et al., 2012). Urban sustainability, however, seems to require radical and rapid transformation (Kennedy et al., 2007; Rockström et al., 2009). In the face of social-ecological tipping points and persistent crises, many nanotechnologies might just not be impactful or realized rapidly enough—in particular when accounting for necessary anticipation and precaution (Hällström, 2008; Brown, 2009). Some nano-enhancements might even end up consolidating adverse path dependencies by providing incremental improvements to urban technologies and structures that are unsustainable in the first place, for example, self-cleaning nano-coatings for buildings below energy and environmental design standards; nano-filtration products that accelerate unsustainable groundwater extraction; automotive nano-enhancements (e.g., motor oil) that sustain urban car-dependency. Path dependencies are further entrenched by end-of-pipe nanotechnologies, e.g., water or air cleaning devices. Those devices divert attention from the root causes of pollution and contamination (patterns of production, distribution, and consumption). Sustainability scholars and professionals agree that upstream approaches addressing these *drivers* of pollution and contamination outmatch end-of-pipe approaches regarding effectiveness and efficiency (Kates et al., 2001; Maxwell and van der Vorst, 2003). End-of-pipe approaches should be seen as at best stop-gaps rather than solutions.

Social Amplification of Risk

From the discourse on nuclear power, genetically modified organisms, and other "controversial" technologies, we have learned that public risk perception and technical risk assessment regularly collide (Pidgeon et al., 2009). In our case, this leads to the questions: who is willing to use or support the use of urban nanotechnologies; do we see benefits or risks becoming dominant in the public discourse; and what roles do worldviews and information play in this dynamic (Kahan et al., 2009). While the complications of risk assessment and management increase with those questions, it is also clear that technological breakthrough and decline are not only, or even predominantly, based on economic reasoning and expert-based assessments (Barben, 2010). Public risk perception plays a vital role for technologies to succeed or fail. If not appropriately elicited and deliberated, the perceived risks might become amplified to the extent that moratoria against particular technologies get implemented; some nanotechnological applications relevant for cities such as food applications might become candidates for such amplifications (Siegrist et al., 2007; Satterfield et al., 2009; Priest et al., 2010). The critical perception of nanotechnologies extends beyond perceived health and environmental risks. Other social risks might raise concerns as well, such as threats to employment, existing economic and social structures, "human nature," and so forth (Besley et al., 2008; Priest et al., 2010).

Additional aspects need to be considered that contest some of the promises urban nanotechnologies seem to offer. For example, while the threat of the almost inevitable accidents that emerge from the complexity of large-scale technological systems (Perrow, 1984) may be quite distant for most nanotechnologies, the related worries of the fate of stored nanomaterials in the case of fires, spills, or other accidental or intentional release has contributed––in the absence of wider standards or information––in some cities in the United States to the exploration and/or development of local regulations for the use of nanomaterials (Barandiaran, 2007; City of Berkeley, 2007).

Exploring the Nano-Enhanced City and Its Sustainability-Oriented Governance

An ongoing research program at the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) explores the nano-enhanced city and its governance (Foley and Wiek, 2012; Wiek, Guston, et al., 2012). CNS-ASU is funded

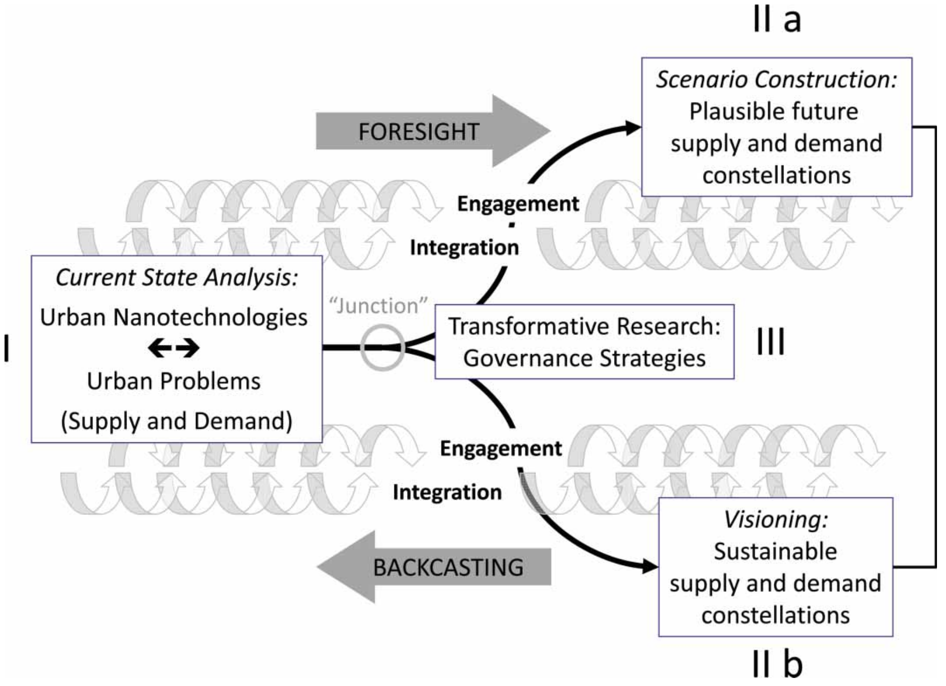

Figure 1.: Procedural model combining transformational sustainability science and anticipatory governance principles. Research passes through three modules (I, IIa, IIb, III) while facilitating public engagement and knowledge integration across disciplines throughout the research process (adapted from Wiek, 2011).

through the National Science Foundation and the research program on "Nano and the City" runs from 2010–2015. Despite exploring the nano-enhanced city in general, the program is focused on the Phoenix Metropolitan Area, Arizona for reasons of feasibility and demonstration. Key partners are government officials, business associations, non-profit organizations, and community members from across the city. The program combines the principles of anticipatory governance with transformational sustainability science to overcome the entrenched operational paradigms described above. Anticipatory governance provides a set of principles on how to collectively imagine, deliberate, design, and influence the development of emerging technologies (Guston and Sarewitz, 2002; Barben et al., 2008; Guston, 2008; Wiek, Guston, et al., 2012); transformational sustainability science provides a normative framework and a procedural template on how to apply those principles in a structured and goal-oriented way (Sarewitz et al., 2010; Wiek, 2011; Wiek, Ness, et al., 2012). We outline the key components of the combined approach in Figure 1.

Current State Analysis of Supply and Demand

On the supply side, we review the spectrum of emerging urban nanotechnologies, key stakeholders, and the mechanisms through which these technologies are governed in the city (Foley and Wiek, 2012). On the demand side, we review sustainability challenges cities struggle with, who is affected by them, what causal structures are involved in their persistence, etc. (Evans, 2002; Kennedy et al., 2007). We then explore how to "reconcile supply and demand" (Sarewitz and Pielke, 2007) by identifying the points where nanotechnology intervenes in the urban problem constellations (Wiek, Foley, et al., 2012). This involves holistically assessing nanotechnology's contribution to problem mitigation, associated costs, alternative solution options, and requirements for governance. Initial study results illustrate the disruptive technology failure and the current dominance of end-of-pipe nanotechnologies (Wiek, Foley, et al., 2012). The results are captured in the *Nanotechnologies in City Environments* (NICE) database (http://nice.asu.edu), which allows searching and commenting on urban nanotechnologies' functionality, mechanism, potential benefits and hazards, related urban sustainability problems, and developmental state.

Foresight

In order to overcome path dependencies and to deliberate and pursue alternative options in a pro-active fashion, participatory foresight research is conducted exploring the constellations of supply and demand with a long-term perspective of roughly 25 years. Building on previous foresight research (Selin, 2008; Wiek, Lang, et al., 2008; Wiek, Gasser, et al., 2009; Selin and Hudson, 2010), the scenario study explores grand architectural possibilities, new social dynamics, emerging patterns of benefit/risk perception, surprises in governance, and potential accidents from a systemic perspective. The short scenario vignettes above illustrate how the program intends to escape the reactive risk paradigm through anticipation of possibilities and challenges in the nano-enhanced city of the future. The value-oriented perspective on these future images, as envisioned through anticipatory governance and sustainability, reveals their relevance for sustainability, or lack thereof, and explicates the expected benefits and costs from a comprehensive perspective.

Backcasting Governance Strategies

On the basis of the previous two modules, we engage in backcasting, crafting, and testing strategies for anticipatory governance of urban nanotechnologies. We explore and co-construct those governance arrangements that seem to be conducive for avoiding undesirable futures and enabling the desired ones (Foley and Wiek, 2012). The exploration goes into innovative types of networks, tactics, roles, and responsibilities of different stakeholder groups, that would overcome the outlined market and governmental failures in the implementation of those urban visions that have been crafted as sustainable and desirable and the avoidance of those identified as not sustainable and undesirable (Wiek, Zemp, et al., 2007).

Engagement

In the three modules, we facilitate stakeholder engagement through real-world experiences and in virtual environments (Al-Kodmany, 2001). Preferences, expectations, potential benefits, and concerns related to nanotechnologies are often contested and vary greatly among different stakeholder groups as well as over time (Scheufele et al., 2007; Selin, 2007; Siegrist et al., 2007; Kahan et al., 2009). As stakeholder groups change dynamically, stakeholder selection and engagement is designed flexibly and is adapted over the course of the research program (Delgado et al., 2011). We conduct public events to map the diversity of perspectives and deliberate on the opportunities and risks of urban nanotechnologies before and while they become real (Wintle et al., 2007; Foley and Wiek, 2012). Urban nanotechnologies are not suddenly appearing, fully developed and entrenched, but they evolve incrementally and somewhat invisibly. The lack of deliberation leaves divergences unrevealed, undermining collaborative efforts and eventually leading to a social amplification of risk. Public engagement on nanotechnology issues, however, faces challenges of justification and design (Delgado et al., 2011). Pursuing such engagement in explicitly place-based, iconic settings (contextualization) mitigates some of these challenges: such familiar settings are prone to a greater willingness to engage (people care about their city), more meaningful engagement processes (people understand the functionality and implications), and tangible outcomes (desirable and sustainable versions of the nano-enhanced city). Therefore, this research program largely focuses its participatory research on Phoenix; yet, it is linked to CNS-ASU's larger engagement across six other US cities in pursuit of generalizing insights on the future of urban nanotechnologies (Selin and Boradkar, 2010; Davies et al., 2012).

Integration

We build on CNS-ASU's successful project on "socio-technical integration research" (Fisher, 2012) in which researchers from the humanities and social sciences were placed in science and engineering laboratories to engage the researchers there in dialogues about responsible innovation. Analogously, we plan on circulating researchers among an academic laboratory, a private development facility, and a public sector agency to follow urban nanotechnologies across the innovation pathway. The Center also sponsors a studio for "integrated teams" of design, engineers, and sustainability students, to explore the future of urban nanotechnologies across different disciplinary perspectives.

The research program addresses challenging questions about the role and support of nanotechnology innovations, which although economically feasible and profitable in the short-term might not contribute significantly to the sustainability of cities over the long run. Given the enormity of visions for urban nanotechnologies, the urgency of the challenges our cities face, and the critical limits on resources and capacities for coping, joint and coordinated efforts across the society, which pursue new approaches to stimulating sustainable change, offer our best chances for responsible nanotechnology innovation.

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Note

1. We follow the US National Nanotechnology Initiative (NNI) defining nanotechnology as "encompassing the science, engineering, and technology related to the understanding and control of matter at the length scale of approximately 1–100 nanometers. [...] nanotechnology is not merely working with matter at the nanoscale, but also research and development of materials, devices, and systems that have novel properties and functions due to their nanoscale dimensions and components" (PCAST, 2005).

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