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PERSPECTIVES

Nanotechnology for sustainability: what does nanotechnology offer to address complex sustainability problems?

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Abstract Nanotechnology is widely associated with the promise of positively contributing to sustainability. However, this view often focuses on end-of-pipe applications, for instance, for water purification or energy efficiency, and relies on a narrow concept of sustainability. Approaching sustainability problems and solution options from a comprehensive and systemic perspective instead may yield quite different conclusions about the contribution of nanotechnology to sustainability. This study conceptualizes sustainability problems as complex constellations with several potential intervention points and amenable to different solution options. The study presents results from interdisciplinary workshops and literature reviews that appraise the contribution of the selected nanotechnologies to mitigate such problems. The study focuses exemplarily on the urban context to make the appraisals tangible and relevant. The solution potential of nanotechnology is explored not only for well-known urban sustainability problems such as water contamination and energy use but also for less obvious ones such as childhood obesity. Results indicate not only potentials but also limitations of nanotechnology's contribution to sustainability and can inform anticipatory governance of nanotechnology in general, and in the urban context in particular.

Keywords Nanotechnology · Sustainability · Complex problems · Problem solving · Intervention research · Anticipatory governance

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Introduction

Nanotechnology is often touted as an important contributor to sustainability. Nobel laureate 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 and 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 and 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 and Dickson 2003; Komiyama and 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 and 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 <10 % of nanotechnology applications currently patented (Lobo and 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 followup projects (Wiek et al. 2010; Wiek and 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): "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 and Guston 2010; Wiek et al. 2012b; Wiek et al. in press).

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 and 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 and 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. in press).

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. in press).

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.

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. in press). Based on a previous study (Wiek and 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

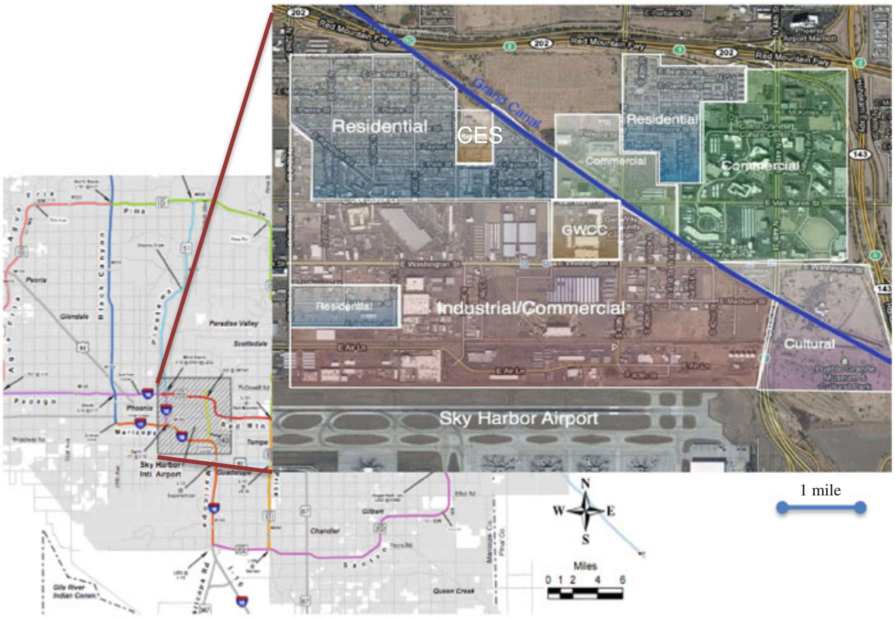

Fig. 1 Gateway Community Corridor in metropolitan Phoenix. *GWCC* Gateway Community College, *CES* Crockett Elementary School. *Note* The zoning demarcations are based on fieldwork and do not necessarily match published city records

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 and Bryck 2011), high-tech economic development in the area (Discovery Triangle 2011), proposals seeking to re-invent 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.

Results

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 and 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 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 semi-conductor 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 semi-conductor 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

Table 1 Basic structure of urban sustainability problems

Title	Causing activities	Underlying drivers and actors	Adverse effects (AE) and impacted populations (IP)	Prevalence indicators and sources
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); biologic 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)	Groundwater contaminated at M52 site: >800 billion gallons (annually >1 billion gallons are pumped and treated) Toxics released at M52 site: 93,000 TCE gallons (ADEQ 2006). Area 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 2010a)
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; economic constraints	AE: Early on-set diabetes; cardio-vascular 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 (16 years 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: 179 g (1,600 calories) (Hiza and Bente 2007) [USDA/HHS recommendation: 25–35 % of caloric intake or 500–1,120 based on recommended caloric intake below] Average caloric intake per person as nation: 3,900 cal (Hiza and Bente 2007) [USDA/HHS recommendation: 2,000 calories per person per day, up to 3,200 in adolescent males]

Table 1 continued

Title	Causing activities	Underlying drivers and actors	Adverse effects (AE) and impacted populations (IP)	Prevalence indicators and sources
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)

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 Fig. 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 and 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

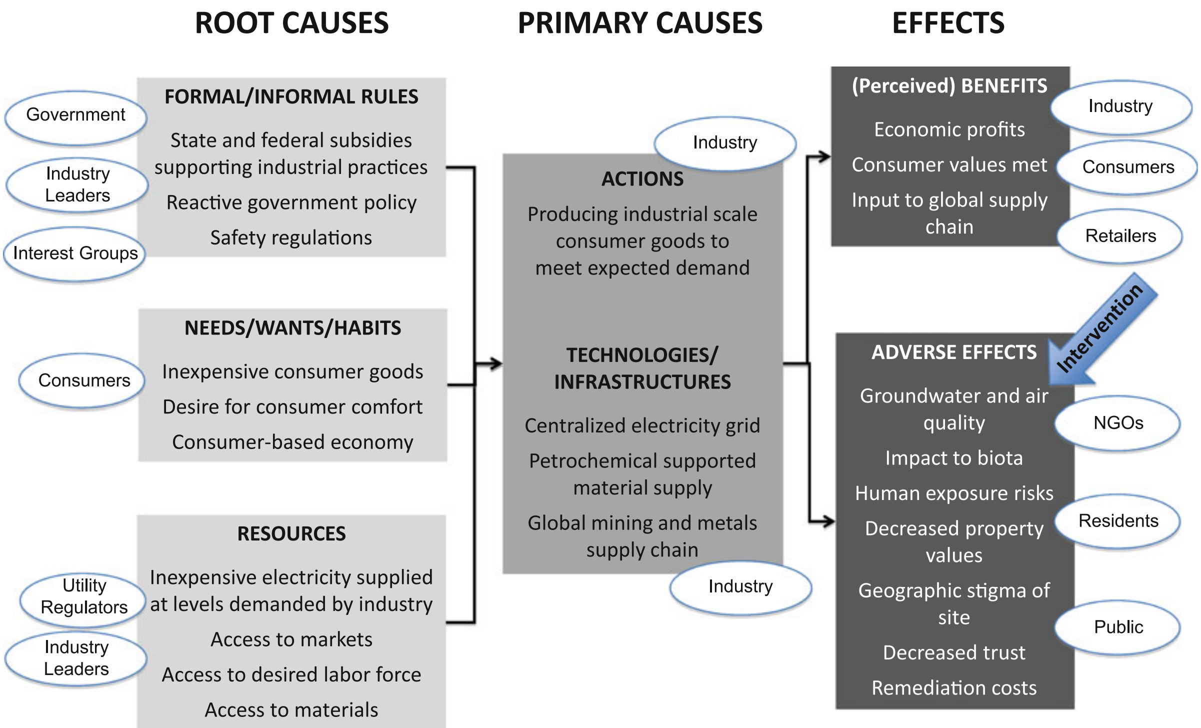

Fig. 2 Problem constellation of water contamination at the M52 superfund site with the proposed intervention point of water purification

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 and 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 (Lightwood et al. 2009).

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

Table 2 Profiles of nanotechnologies applicable to selected urban sustainability challenges (for details visit: http://nice.asu.edu)

Urban sustainability challenge	Nanotechnology function	Nanotechnology substance; and mechanism	Potential full-scale benefits	Potential full-scale life cycle impacts	Development stage	Substitute for:	Sources/references
Water contamination	Water decontamination	nZVI particle; active	nZVI is injected within a slurry to catalyze organo-chlorinated solvents in situ.	Life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2009)	Engineering	Pump and treat with activated Carbon	Watlington (2005). Zhang (2005). Valli et al. (2010), EPA (2011e), Ela et al. (2011)
Water contamination	Water desalinization	Polydi-methyl-siloxane compound; passive	Ion polarization creates functional junction to separate desalinated water from enriched brine.	Life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2009)	Scientific Proof of Concept	Macro-porous filters and evaporators	Kim et al. (2010), Tarabara (2010)
Air contamination	Air purification	Carbon nanotubes (CNTs) and TiO_2; passive	Cleans indoor air to remove contaminants.	Unknown Some evidence of lung impacts from air borne CNTs (Kimbrell 2009)	Scientific Proof of Concept	Macroporous filters	Woan et al. (2009), Oh et al. (2009)
Air contamination	Vapor detectors	SnO_2 metal oxide; passive	Contaminant gas surface reacts with metal oxide sensor.	Life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2009).	Engineering	Electro-chemical gas sensors	Graf et al. (2006), Wang et al. (2010), Waitz et al. (2010)
Health	Food additives	TiO_2 particle; passive	Titanium dioxide is a transparent coating preventing microbial growth.	Oral ingestions of TiO_2 particles in lab mice has lead to health concerns about bio-distribution and acute toxicity (Wang et al. 2007)	Commercial	Shelf life expiration and product disposal	Mihee et al. (2007), Wang et al. (2004), Kuzma and Verhage (2006)
Health	Food additives	Nanocapsule structure; passive	Omega-3 fatty acids are encapsulated and inserted into carbohydrates.	Life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2009)	Scientific Proof of concept	Balanced diet by varied food selection.	Siegrist Siegrist et al. (2007), Robson (2011), Eldaw (2011)
Energy efficiency	Energy storage	Fluorinated polymers (FPA) and alkaline metals; active	Energy storage with denser and non-aqueous (ionic air) electrolyte.	Life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2009)	Scientific Proof of Concept	Aqueous phase electrolyte solutions.	Friesen and Buttry (2010), Salloum et al. (2008), Mickelson (2011)

Table 2 continued

Urban sustainability challenge	Nanotechnology function	Nanotechnology substance; and mechanism	Potential full-scale benefits	Potential full-scale life cycle impacts	Development stage	Substitute for:	Sources/references
Energy efficiency	Photo-voltaics	CdTe or GaAs; passive	Full-scale installation would produce demanded power required by Phoenix.	Life cycle CO_2 equivalent emissions estimated at 90–300 times lower than coal-fired power plant in studies (Fthenakis et al. 2008)	Ubiquitous, but not available	Fossil, nuclear, and biomass combustion	Kato et al. (2001), Noufi and Zweibel (2006), Tettey et al. (2010)
Energy efficiency	Industrial catalysis	Zeolite L particle; active	Zeolite L nanoporous catalyzes bulk particles into reformed compounds.	Life cycle analysis proposed by EPA and university researchers (Eason et al. 2011; Wiesner et al. 2009)	Scientific Proof of Concept	Bulk Catalysts	Hu et al. (2011), Bernardo et al. (2009)
Energy efficiency	LED lighting (nano-enhanced)	Nonacene compound; passive	Organic light emitting diodes that can be affixed by printing on materials surface.	Proposed research on-going at Green Launching Pad (Brooks 2011)	Scientific Proof of Concept,	Fluorescent and filament lighting	Purushothaman et al. (2011), Gao et al. (2011), Kaur et al. (2010)

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 1.

Nanotechnology applications (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 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).

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 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

Table 3 Nanotechnology applications as intervention strategies for complex urban sustainability problems

Case study	Systemic intervention points	Mechanism	Decision-makers	Decision process	Barrier(s)	Required resources	Effectiveness	Efficacy	Current invention strategy	Sources/references
Water contamination (M52 Superfund Site)	Remediate contaminated groundwater Provision air filtration	Contaminant removal post-release	Regulatory agencies, responsible parties, community members	Formal federal decision-making process	Decision-making Process; Test site validation; Acceptance by parties; Sunk costs in current technology;	Unknown energy and materials costs.	Pilot stage in situ testing for nZVI slurry. Lab scale proof of concept for CNT air filtration.	Pilot test reported 82–96 % reduction in TCE. No in situ testing of CNT air filters.	Both use known activated carbon based technology	Chang et al. (2010), EPA (2011e), Watlington (2005)
Childhood Obesity	Alleviate food deserts by lengthening storability Enhancement nutrition with food additives	Industrial packaging using titanium dioxide as bacteria disinfectant Insertion of omega-3 fatty acids into carbohydrates	Industrial agriculture packaging, distributers, consumers, and FDA	Formal regulations. FDA approved bulk-TiO_2 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 TiO_2 coated cellophane. Capsulation of omega-3 in carbohydrates. Unknown energy and materials costs	*E. coli*, *Salmonella typhimurium*, and *B. cereus* eliminated by TiO_2 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 historic food safety issues (i.e., recalls) and product testing. Nutrition information based on historic tests.	Wang et al. (2004, 2007), Mihee et al. (2007), Kuzma and Verhage (2006), Siegrist et al. (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-conductor 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 regulated 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, available energy efficiency subsidies	Production, material costs, financing, political will, addition al storage capacity, and net energy are not all known.	Currently 7.3–10.2 efficiency is reported for thin-film photo-voltaic. Price point is two times existing sources. LEDs provides high quality lumens with reduced energy demand.	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.	Kato et al. (2001), Fthenakis et al. (2008), Noufi and Zweibel (2006), Tettey et al. (2010), Hatch-Miller et al. (2006)

answer the guiding question on what nanotechnology offers to address complex sustainability problems.

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 amendable 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 eco-toxicity 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. 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 and 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 clean-up 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.

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 TiO_2 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 TiO_2-coated packaging (Robinson and Morrison 2009). The second intervention is the construction of nutritionally enhanced carbohydrates (a food staple in US diets) with omega-3 fatty acids (Robinson and 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 TiO_2 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, organochlorine 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 and 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 which 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.

Addressing the lack of renewable energy

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 and 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 and 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 home owners 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 and 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.

Discussion

Our study 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 and 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 TiO_2 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.

Conclusions

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.

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