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Urban Heat Stress Vulnerability in the U.S. Southwest: The Role of Sociotechnical Systems

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Academic Editors: Patricia Romero-Lankao, Olga Wilhelmi and Mary Hayden
Received: 18 May 2016; Accepted: 17 August 2016; Published: 25 August 2016

Abstract: Heat vulnerability of urban populations is becoming a major issue of concern with climate change, particularly in the cities of the Southwest United States. In this article we discuss the importance of understanding coupled social and technical systems, how they constitute one another, and how they form the conditions and circumstances in which people experience heat. We discuss the particular situation of Los Angeles and Maricopa Counties, their urban form and the electric grid. We show how vulnerable populations are created by virtue of the age and construction of buildings, the morphology of roads and distribution of buildings on the landscape. Further, the regulatory infrastructure of electricity generation and distribution also contributes to creating differential vulnerability. We contribute to a better understanding of the importance of sociotechnical systems. Social infrastructure includes codes, conventions, rules and regulations; technical systems are the hard systems of pipes, wires, buildings, roads, and power plants. These interact to create lock-in that is an obstacle to addressing issues such as urban heat stress in a novel and equitable manner.

Keywords: urban heat; vulnerability; socio-technical systems

1. Introduction

Heat vulnerability of urban populations is becoming a major issue of concern including in the American Southwest, where extreme heat events are forecast to increase significantly under climate change in the coming century [1]. In this article we point to the importance of coupled social and technical systems (sociotechnical systems), as they form the conditions and circumstances in which people experience urban heat. That is to say, such systems produce the urban fabric of daily life, and thus how people live. In this article, we explore the combination of social and technical factors that create or amplify vulnerability to heat events in southwest cities. Sociotechnical systems include the social organization and systems of city and other governmental regulatory organizations and the rules, regulations, codes that they both promulgate and follow, and the technical systems of informatics, roads, power plants, wires, pipes, buildings, and more [2].

Heat waves, particularly extreme heat events, lead to increased mortality, morbidity, emergency room visits and hospitalizations [3–8]. Heat waves and lack of access to cooling result in significant morbidity and mortality effects. We wish to highlight that, like for other systems [9,10], technical infrastructural systems, such as buildings and urban morphology, coupled with energy distribution systems and the ways they are managed, can lead to unanticipated outcomes, such as increased heat vulnerability. Given the certainty of increased heat days globally and in the U.S. Southwest, paying attention to such socio technical systems and their impacts, can begin to point to urban systems lock-ins (see Unruh 2000 [11] on carbon lock-in) and the need to de-couple systems to enhance urban sustainability and adaptation to climate impacts. Moreover, as Klinenberg (2000) [12] explains of the 1995 Chicago heatwave that killed over 700 people, there is a complex and interacting set of conditions from social, institutional, and technical forces, which can lead to catastrophic outcomes. Physical technical systems are nested and tiered from the neighborhood to the grid, how they are developed and regulated, and create interacting, reinforcing systems [11] that can lead to increased vulnerability, particularly for disadvantaged populations. The impacts from heat on urban populations are, in many ways, artifacts of technical systems, such as building thermal characteristics, availability of affordable and reliable electricity, the characteristics of physical surfaces, parks and greening, and overall, urban morphology, nested within the larger electric grid system. These hard infrastructures are a result of, and, in turn, affect the soft infrastructures of regulation, codes, conventions, real estate markets, and more—including more intangible infrastructures such as social networks. Importantly, these imbricated systems will have specific national, regional and local characteristics, pointing to the importance of precision.

Specifically, the 2006 California heat wave resulted in 16,000 additional emergency room visits and 1200 additional hospitalizations [6]. The European heat wave of 2003 led to 70,000 excess deaths [13]. In a study of nine California counties from May through September of 1999–2003, researchers found that for every 10 °F increase in ambient temperature, there was a 2.6% increase in cardiovascular mortality [14].

Much research has focused on understanding the social aspects of vulnerability to natural hazards. For example, Blaikie et al. define vulnerability as "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard" [15] (p. 9). Turner et al. (2003) [16] take a more theoretical approach, investigating multiple, interacting stressors, the order and impact of those stressors, and the varied responses to stressors, including institutional and structural variables. There is a significant literature on public health and social vulnerability [3,14,17–21], as well as socio-economic factors and vulnerability [12,22,23].

Social vulnerability to heat research has examined the socio-economic characteristics of vulnerable population sub-groups including factors such as older age, low income, social isolation, and presence of chronic disease that increase the risk for morbidity and mortality during heat events [6,24–29]. Infrastructure contributions to higher heat in urban areas has also received study, including how the built environment increases the urban heat island (UHI) in cities, for example, through street design [30], the impact of albedo—the reflectivity of the hard infrastructure of the city will affect heat in cities, the darker the surfaces, the more heat builds up during the day—[31–33], and tree canopy coverage may also create a confounding factor [34–37]. City specific UHI studies have also been conducted—Montreal and Vancouver (1975), Phoenix [27,38] and others. Research has also been conducted, as early as the 1970s, before concerns about climate impacts, looking at the relationship between city size and the UHI [39]. In addition, recently there has been interest in how buildings themselves may increase vulnerability, as in the case of Hurricane Sandy when lack of electricity marooned elderly and ill residents in high-rise buildings [40]. In this case, an already vulnerable population—the elderly—was made more vulnerable due to the built environment. However, there is insufficient analysis of how socio-economic, technical and regulatory systems may work together to create or enhance vulnerability to heat. Our examination of the U.S. Southwest shows the nested and tiered scalar attributes of the sociotechnical systems that contribute to creating unequal exposure to urban heat in cities in the southwest.

2. The Case of the Southwest U.S.

The southwest is warming. Average daily temperatures for the 2001–2010 decade were the highest in the twentieth century, and, since 1950, the period has been the warmest in the past 600 years [41]. Stream flows in the Sacramento, San Joaquin Rivers, Upper Colorado, Rio Grande and Great Basin were as much as 37% lower during this same period, not including California's current historic drought. Climate is projected to continue to warm, with longer and hotter heat waves in the summer [42]. Further, another major change that is anticipated is an increase in nighttime versus daytime projected heat wave occurrences, in part due to elevated humidity that will diminish nighttime respite from heat [43]. Extreme heat events are expected to occur with greater frequency, duration and intensity as atmospheric concentrations of greenhouse gases increase [44].

Studies have predicted increases in frequency, duration, and severity of extreme heat events [45–48]. Using a ten-year drought exercise in the southwest, higher incidences of extreme heat and drought were estimated to reduce average summertime electricity generating capacity—for water-dependent power stations (45% of capacity)—by 1.1%–3.0% with reductions of up to 7.2%–8.8% [49]. It is now evident that frequent extreme heat events [50] will exacerbate extreme heat degree-days in the U.S., and especially in the southwest and will negatively impact the effectiveness of the grid itself. This is because roughly 68% of California's and 93% of Arizona's electricity is generated from water-intense fuel sources, including coal, natural gas and nuclear energy [51]. Precipitation will affect water availability for these types of electricity generating plants. Coupled with the increase in numbers and intensity of heat spells that are projected to increase electricity demand between 6% and 22% in California in the next 80 years [33], especially if there are no substantial changes in urban morphology, there is a looming shortage of potential electricity generation from traditional sources [49]. While solar electricity generation is growing in capacity, issues of grid integration still prevail, and some concentrated PV technologies also require water. Further, any increases in air conditioning, powered by solar electricity or not, will add to the urban heat burden by virtue of the heat expended in running AC motors. How to respond to these conditions, fewer water resources but higher cooling needs, requires investigating the interwoven interactions among technical systems (power generation, water systems), the existing urban fabric and the rules and codes that guide land development and urban morphology (buildings, roads, access, urban growth, vegetation, cooling centers), and the nested and tiered regulatory purview of electricity generation itself.

3. Vulnerability

A number of articles have established the genealogy of vulnerability research, starting with natural hazards research. Historically hazards research placed emphasis on the natural phenomenon itself. Risk was understood to be most strongly associated with the exposure to the hazard, including the probability of the hazard occurring and the place-based exposure to the hazard. White and Haas [52] critiqued early vulnerability work for insufficiently taking into account human factors involved in creating hazards, including social, political and economic factors. At that time, research on disasters was dominated by physical scientists and engineers. Little attempt had been made to better understand the economic, social and political decisions that created exposure to hazards, such as allowing the construction of housing on flood plains or earthquake faults and the subsequent human impacts of extreme events. White and Haas advanced the notion that rather than picking up the pieces after the extreme event, the nation could employ better planning, land-use controls, and other preventive and mitigation measures to reduce the risk in the first place.

This critique led to the birth of a hazards community who began to develop an interdisciplinary approach to research and management of natural disasters from multiple fields [53]. Social vulnerability theorists understood that groups of people or populations were vulnerable because they lacked the ability or had reduced capacity to prepare, respond, adapt or recover from a particular harmful stressor. Theorists pointed out that characteristics of vulnerable populations can be intrinsic, such as physical disability, or exogenous: lack of resources to respond due to poverty, for example. Sociopolitical systems can add to group's vulnerabilities by marginalizing them politically, isolating them from mass communications, developing rules that don't take certain populations into account, or by ignoring cultural differences. Bohle, Downing and Watts [54] described human vulnerability as an aggregate measure of human welfare that integrates environmental, social, economic and political exposure to a range of potential harmful perturbations—but not infrastructural factors. This exposure is unevenly distributed, affecting those who possess the most limited coping capacity the most. Vulnerability is multi-layered and multidimensional and inherited from political, economic and institutional conditions under which people find themselves.

Cutter et al. [25] famously developed a social vulnerability index (SoVI) that integrates place with social aspects of vulnerability and that subsequently has been applied across a number of cities and regions [55–58]. Eakin and Luers [23] highlighted the need to take into consideration not just how to identify populations and peoples at risk and offer viable solutions for their vulnerabilities, but that economic development, disaster policy and natural resource management were important to consider as well. They pointed to vulnerability as a relative concept created by conditions of social justice, equity and opportunity—vulnerable populations tend to be lower income and have fewer opportunities than others (p. 367). Heat vulnerability specifically, has been increasingly taken up by health departments, though in in major counties in the southwest U.S. such as Maricopa County (home of the Phoenix metropolitan area) and Los Angeles County, much of the effort relies on cooling facilities that still remain scarce [59,60]. It is beyond the scope of this paper to conduct a national and international review of heat vulnerability planning and best practices, as these will differ by urban morphology, local government fiscal capacity, state involvement and more. Rather, our focus is to highlight how, at nested and tiered scales, urban morphology and its codes, rules and regulations, combined with the grid itself, can create the circumstances of increased heat vulnerability to which heat planning must respond—and which may be different in different national contexts. For example, in France there is a strong reliance on nuclear power, and the grid is both centralized and national. We turn next to a brief description of sociotechnical systems.

4. Sociotechnical Systems

First interest in sociotechnical systems can be found in Mumford's *Technics and Civilization* [61], where he suggested that material and symbolic cultures of society were intertwined in a complex web of mutual causality. Material aspects of society can be thought of as the technical infrastructure, and the symbolic falls in the realm of the social infrastructure. Singer [62] described them as co-producers of each other [63]. Technical infrastructure relies on a set of rules, codes, standards and regulations (social infrastructure) that organize how they are built and regularize them [64]. For example, successful airports are built following standards to ensure planes can land and take off safely. These are developed by an international standards setting organization. Road standards in the U.S. are codified by the American Association of State Highway and Transportation Officials (AASHTO), of which standards are then implemented by road builders and public works departments. These standards now stand in the way of such newer efforts like complete streets that include green infrastructure, or changing levels of service requirements as they challenge the status quo practices. Of course, once the road infrastructure is built, it creates obdurate infrastructure, hard and expensive to modify which today we know is a strong contributor to the urban heat island effect [65]. This type of co-production is intrinsic to all systems—sewage treatment plants, power plants, hospitals and the electricity grid, which operates at nested scales. None of the hard infrastructure, or technical systems, can be built without the soft infrastructures that guide them according to socially agreed upon standards or rules. At the same time, once they are built, they create a kind of lock-in and path dependency [11]); shifting to a different technical infrastructure is expensive, and requires a change in habits, say changing from air travel to the train, as well as rules, laws, financing and more. The mutual constitution of the social and technological is the basis of the term sociotechnical.

This stands apart from technological determinism as it implies an interactive dynamic [66]. Technological determinists tend to see technical systems as sui generis, and implementable without a social infrastructure. However, ideas for the technologies come from society and perceived social needs; funding for technological development, financing for its implementation, regulation to assure it is safe, are all components of successful technologies. Thus there are deep and inextricable interdependencies between social and technical systems. There is a growing literature on sociotechnical aspects of cities. Hughes' *Networks of Power* [67] was a seminal discussion of the development of the national electricity grid in the U.S., pointing out that "[P]ower systems reflect and influence the context, but they also develop an internal dynamic. Therefore, the history of evolving power systems requires attention not only to the forces at work within a given context but to the internal dynamics of a developing technological system as well" (p. 2).

In the domain of energy, climate and sustainability transitions to low carbon, increasing attention is increasingly being paid to infrastructure and the political nature of the processes through which infrastructure systems are maintained that are simultaneously local, global, human, physical, cultural and organic [68,69]. City sociotechnical infrastructures have become increasingly interconnected over time and the complexity of this interconnectedness is often poorly understood. Cities rely on power systems and water delivery systems that are often centralized and can draw resources from far off from far flung regions. Centralized systems can increase vulnerability, not just of the systems themselves (e.g., electricity generated by hydro in a region susceptible to drought), but then, cascading to city residents, and further affecting the most disadvantaged. That, in itself, impacts the size, centralization and efficiency of big systems [2]. For now, understanding the systems as they exist is the essential first step. We now turn to the scalar interconnections of power systems and urban morphology.

4.1. SocioPower Systems—Scalar Interdependencies

Power systems, developed largely in the 20th century, tend to rely on centralized power plants, like natural gas or coal fired power plants, or dams. They are part of an energy grid, regulated by a complex set of institutions that, in the U.S. include federal agencies such as the Federal Energy Regulatory Commission (FERC), which sets the rates and service standards for most bulk power transmission, licenses both hydro and nuclear power plants and enforces reliability standards developed by the North American Electric Reliability Corporation (NERC). There are also regional entities, such as the Western Electricity Coordinating Council (WECC), which promotes bulk electric system reliability in the Western Interconnection area that provides power to the Western U.S. The WECC promotes grid reliability and is responsible for compliance monitoring and enforcement, and it further has balancing authorities among sources of power. Some smaller grid areas within each NERC reliability planning area are managed by individual utilities, mostly large investor-owned, and some by the federal power marketing agencies. In the Western interconnection, there is no region-wide Regional Transmission Operator or Independent System Operator (ISO) (other than California), to coordinate power distribution and reliability (in contrast to other parts of the county), so the individual control-area operators coordinate with each other to ensure region-wide reliability of service [70]. Further, there are also state regulators that adopt construction standards for retail distribution facilities, quality of service standards, the prices and terms of service for electricity provided by investor-owned utilities. These are the state Utilities Commissions. There are further rules that regulate the distribution systems at the local scale, and more. In the U.S., investor owned utilities predominate in energy systems. While some, like Southern California Edison in Southern California are parts of international conglomerates, their operations are regional. Southern California also has a number of municipal utilities, including the largest in the country, the Los Angeles Department of Water and Power (LADWP). Each of these has different interties into the larger western grid, and different regulatory structures (municipal utilities are regulated by municipalities, but are nested in the larger grid network with interties for security and resilience). Maricopa County in Arizona, is dominated by an investor owned utility, Arizona Power Service Company (APS).

Different rules and proceedings from the Federal Energy Regulatory Commission to the state PUCs shape the type, price and reliability of energy used in cities. For example, in California, the state's Public Utilities Commission recently decided on a petition by Pacific Gas and Electric (the large investor-owned utility in Northern California) to increase the monthly exit fees by over 100% for customers transferring to local green energy programs [71]. Pacific Gas and Electric wants to discourage local distributed generation that is provided by another utility and emerging Community Choice Aggregation non-profit alternatives. Interestingly, Southern California Edison seems to have been less active in wanting rate increases for domestic solar. APS, however, has been lobbying to increase monthly fees for domestic solar installations in its Maricopa County service area and the Arizona Salt River Project utility has added fees for people adding rooftop solar [72].

The 20th century electricity grid and associated large scale infrastructures that support U.S. cities and that are found in cities, have been brilliantly successful at providing water, heating, cooling, sewage systems and generally safe environments [73]. However, at the turn of the century, with the growing severity of climate change, the imperative to reduce greenhouse gas emissions and impacts of these factors on many cities, these systems are likely no longer appropriate for ensuring the needs of urban populations are met, and may, in fact be creating populations vulnerable to increasing urban heat, among other impacts. For instance, many of the systems and regulatory regimes today have not been designed to withstand climate impacts, recover quickly, or adapt to changed circumstances. Water dependence of existing power plants in the southwest is a clear example. Water availability into the future will most likely fluctuate significantly, deeply affecting the ability of those power plants to effectively deliver reliable electricity. But there is insufficient back up in the grid to make up for this, especially on an either recurrent or long-term basis. This problem is clearly one that sits at the level of the scalar energy infrastructure and its regulation from the WECC and the Western Interconnection to potential distributed generation in cities themselves. The awareness of the problem, the decisions that are being made and the movement toward new regulatory regimes may all be taking place, but are highly contested. However, decisions will cascade through the electricity system all the way down to individual people in specific buildings and their ability to cope with heat events.

Sociotechnical systems co-evolve, and this occurs in political and technical settings. Uncoupling different pieces—the hard technical systems and examining their viability—and the social regulatory/institutional and private investment juggernaut—to unpack the path dependent and reinforcing patterns of the status quo is primordial to change. To add to the complexity, this will need to occur at multiple and interacting scales, from the building to the grid, to the power plants, and examined for their organization and impacts at each scale. There is no question that changes will affect current vested interests across the board and that there will be value propositions regarding the direction of change as well as issues of timing and technologies [74].

The organizational management of the grid, the agencies involved, to date, have no formal methods to account for climate impacts in their development and management plans. Alternative sources of energy, such as distributed generation, for example, as we have seen in Arizona and California, may be resisted by the status quo energy utilities. Public Utilities Commissions, politically appointed bodies, ultimately are the decision makers for private utilities. Regulators are in a position to determine the direction of change relative to power supplies (such as increasing renewables in the face of declining hydro and the need to reduce GHGs) and charges, decisions that are not entirely technical, but involve historical considerations that include longstanding relationships with utilities, and political pressures regarding views on the degree and importance of climate change. As temperature averages are crossed more frequently and for longer periods of time, so too will the impacts of extreme heat on human health [75]. Such decisions will deeply affect the sustainability of cities.

4.2. City Regions in the Southwest

Projections are that over the next century, extreme heat events are estimated to increase by 340%–1800% in Maricopa County, and by 150%–840% in Los Angeles County [42]. This eventuality is situated in a region where cities are relatively new. Los Angeles, Las Vegas, Phoenix and Albuquerque, for example, saw their growth occur in the 20th century. Los Angeles had its major growth spurt post World War II, and Phoenix, Las Vegas and Albuquerque in the latter part of the 20th century. Post-war buildings were regulated for safety, but not for efficiency, so the bulk of these buildings were built to rely on heating and cooling systems, especially since power was inexpensive.

Heat impacts reveal the importance for the individual of specific buildings, streets, and services (such as access to cool malls, libraries, and to transportation to get there). Shaded streets and changing urban albedo can reduce the urban heat island; better built buildings will reduce the need for additional energy expenditures to cool them. But each of these changes requires new objectives, new codes and procedures, new investments. They require commitment to mitigating urban heat under conditions of climate change in contrast to simply producing more electricity to power air conditioning. Nothing short of systematic and conscientious integration of new rules and techniques, the elaboration of a new sociotechnical regime, will achieve the transformation needed to mitigate the worse effects of a changed climate on southwest cities and their population.

An emphasis on determining who is likely to be the most impacted, and starting with those people, might be the first step forward. However, any steps will require revisions in the coupled sociotechnical system at multiple scales: Neighborhood, city, state and beyond. Today, and especially in California since 1978, building codes require greater attention to building thermal performance, though these standards are not consistent across the southwest, nor do they apply retroactively. Reyna and Chester [76] found that for Los Angeles for example, the majority of buildings were constructed post war. Buildings constructed before California's landmark Title 24 building energy codes, are far less energy efficient per square foot [77]. Older residential buildings tend to be concentrated in lower income neighborhoods, where energy use is lower per capita than in wealthier ones, but the small buildings are poorly insulation, often lack air conditioning and thermal comfort (in Los Angeles). This implies residents are living in leaky, inefficient buildings where they are hot in the summer and cold in the winter, or they must use a lot of energy to compensate.

These newer cities were built in a period of unlimited and inexpensive fossil fuels, land and water. Growth was relatively dense, but land extensive, planned around single-family homes with pockets of multiple family residences, largely oriented toward lower income residents. Such urban morphology contributes to the urban heat island effect (UHI) with broad (and dark) streets and roads little shade as buildings are far apart and there are few if any shade structures or trees [55,78]. Parks are an important and often neglected part of urban infrastructure and can serve as sanctuaries for apartment dwellers, who not only do not have yards, but who also may not have air conditioning. Trees and watered vegetation (when it exists), can offer respite from the warmest days [79] but southwest cities have less tree canopy than cities in more temperate climates. Temperate cites tend to be located in places that were forested while tree canopy in southwest cities is a result of afforestation efforts and must be balanced with water resources [80–82]. Yet, urban shading is a component of cooling the urban atmosphere and an aspect of infrastructure. In water short regions, trees pose problems of maintenance since they must be watered, and street trees are the responsibility of residents. At the same time there are now more research results showing that land-surface temperatures are affected by green-space—trees and vegetation reduce the urban heat island effect in southwest cities. There is evidence that when green spaces are concentrated in a single area their effect can be stronger to mitigate the urban heat island than when dispersed. But much more research needs to be done about distribution of those spaces and their interactions with buildings and paved surfaces [83]. There is also emerging research on southwest cities investigating the impact of urban form on microclimates. Though Spirn [84] early on pointed out that urban morphology has an impact on city climate(s), recent research by Middel et al. [85] in Phoenix found that, at the microscale, urban form had a larger impact on daytime temperatures than vegetation. For cities in the southwest to mitigate the worst effects of heating, changing general plans, zoning, parks and recreation plans, street widths will all need to be investigated for their climate impacts. Changing those rules and codes will have to be done by planning commissions, public works commissions, planning departments and public works departments, and ultimately by elected officials. Again, current patterns create heat vulnerability due to historical legacy effects of how cities were built and then regulated, and income variables that determine where people live and under what conditions.

Thus, each region and locality is going to have its own particular set of variables that modify the relationship between heat and morbidity and mortality and increase vulnerability [14,56,86]. In the southwest as elsewhere in the U.S., poverty and older age consistently turn out to increase vulnerability to extreme heat, but there can be unexpected relationships. Chuang and colleagues found that wealthy, White-Anglo neighborhoods in Phoenix had higher hospital admissions for heat-related illnesses than was predicted by Harlan's heat vulnerability index [87]. Many of these neighborhoods were far from Phoenix's urban core and had high proportions of households that had relocated to the neighborhood in the past five years. This raises another possibility: "sunbirds" are a socially vulnerable group when it comes to extreme heat events, or other confounding effects such as higher propensity to go to hospitals than other populations or being insured. These unknowns illustrate how little researchers understand the ways social contexts influence vulnerability. Furthermore, it demonstrates that each region, and even each locality, may have a spectrum of groups and populations who are most vulnerable to extreme heat in different ways.

Overall, however, heat vulnerability and indices are still in development for southwest cities. Issues such as access, defined as the ability to physically reach a publicly available public cooling center (such as a community center or library) or having affordable home air conditioning, are a function of urban morphology, availability of transit, reliable and cheap electricity, and building thermal characteristics. Research into populations that are traditionally more vulnerable due to income, language exclusion, age, ethnicity and health, and access for southwest cities is beginning to emerge and matched to building characteristics and understanding of electricity markets will provide useful insights. In other words, how those indices interact or intersect with the sociotechnical systems discussed above will be important next steps. Further, distributed solar energy production may also play a role in reducing vulnerability and improving thermal comfort in buildings, if such energy generation can be widely distributed. Cost of the new infrastructure, issues of grid infrastructure and storage are still at the forefront of the transition challenges and, as we have discussed, responses will vary from state to state and from utility to utility. Understanding heat vulnerability in socio-technical systems need to be added to the transition strategy to ensure people's health and safety.

New approaches are needed for understanding the ways socio-economic, physical infrastructure, and institutional (including laws, codes, rules, policies, and norms) factors may affect heat vulnerability in different places and for different populations. Much of current public health programs and city programs such as cooling centers, focus on population intrinsic characteristics including age, existing health conditions, race, and so on. While important, vulnerability analyses that focus on just one aspect of these interdependent system are likely to miss the greater complexity that is driving how people are ultimately vulnerable to climate change. New science is needed to identify how significant infrastructural and institutional variables are in contributing to heat vulnerability. This includes access to affordable air conditioning, the efficient locating of publicly accessible cooled space including county cooling centers, access to reliable and affordable electricity for cooling, and the heat performance of buildings. The energy transition to renewable resources, driven by national and state policy and the utilities are additional factors that affect local populations differently. The cost of energy, incentives for air conditioning or building thermal improvements and how these themselves interact to mitigate vulnerability, or not, is not sufficiently explored.

5. Conclusions

There is a growing interest in sociotechnical systems and how they evolve and work, how they reinforce one another and create path dependencies and lock in. This research is useful in helping frame questions such as climate vulnerability and how it is manifest in specific regions like the U.S. Southwest. There is increased data generation about social and infrastructure factors at finer and finer scales that can greatly help in understanding the vulnerability of individuals and groups to climate impacts in cities to reduce impacts. For the southwest, there are short and long term and scalar issues at play to move toward less climate vulnerable sociotechnical systems. Presently, such mundane but urgent questions as who has access to cooled spaces, how we can provide reliable access to cooled spaces and prioritize infrastructure to protect those who are most at risk, are the first tasks at hand. The longer-term resolution will come from a fine scale (building, street, neighborhood) analysis nested within a larger reform of urban morphology to make cities themselves less hot. That will involve changes in codes, regulations and conventions, as well as the rebuilding the existing hard infrastructure and vastly expanded programs to improve thermal performance of existing buildings. Then, of course, there is the question of the energy system itself and the choices of direction—centralized versus decentralized generation—some artful mix—and the regulatory regimes that achieve those ends [88]. These are multiscaler and multi-time frame pathways that will need to be developed that are nested and tiered in order to increase urban sustainability.

Acknowledgments: This works is made possible by several National Science Foundation grants (Award No. IMEE 1335556, IMEE 1335640, and WSC 1360509, and RIPS 1441352).

Author Contributions: Pincetl led the development of the article and was primary author. All authors contributed to the conceptualization o the project and drafting critical revisions. Chester and Eisenman led the data analysis, interpretation and directed the project.

Conflicts of Interest: The authors declare no conflict of interest.

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