ENERGY AND WATER SUSTAINABILITY: THE ROLE OF URBAN CLIMATE CHANGE FROM METROPOLITAN INFRASTRUCTURE

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ABSTRACT

As recently as 1950, 30% of the world's population lived in urban areas. By the year 2030, 60% of the world's population will live in cities. The science of sustainable development requires the ability to examine and understand the implications of broad and aggregate impacts. This is even more difficult in rapidly urbanizing regions globally where the pace of change itself becomes part of what has to be taken into account in engineering designs, modeling, planning, and policy development. Urbanization is quickly transitioning communities from native vegetation to man-made urban engineered infrastructure. Anthropogenic changes in the characteristics of the land surface can have a marked impact on the partitioning of energy at the surface. This is often manifested in microscale and mesoscale modifications to the thermal properties of the surface and atmosphere and can result in significant increases in temperatures in comparison to adjacent rural regions which, is known as the Urban Heat Island Effect (Urban Heat Island or UHI). The UHI is understood in theory, but its practical engineering and policy implications resist interpretation due to the variations in social, economic and environmental conditions in a given region at a given time.

The findings of this research indicate that the thermal modifications to the climate as result of urbanization have impacted the sustainability of the Phoenix, Arizona region. Overall HVAC electrical consumption for a representative 2,000 ft^2 has increased from 7,888 kWh per year in the 1950's to over 8,873 kWh per year in the 1990's. This also impacts water supply in the arid region as the research finds 6,550 gallons of water is consumed by household for HVAC electricity consumption.[5]

KEYWORDS

Urban Heat Island, electricity, water, metropolitan, infrastructure, urbanization, sustainability

1. INTRODUCTION

As recently as 1950, 30% of the world's population lived in urban areas. By the year 2030, 60% of the world's population will live in cities [1]. The science of sustainable development requires the ability to examine and understand the implications of broad and aggregate impacts. This is even more difficult in rapidly urbanizing regions globally where the pace of change itself becomes part of what has to be taken into account in engineering designs, modeling, planning, and policy development. Urbanization is quickly transitioning communities from native vegetation to man-made urban engineered infrastructure. The urban environment, with its impervious paved surfaces and reduced vegetation, causes less of the incoming radiant energy from the sun to be reflected from urban areas and, likewise, less of this energy is converted to latent energy associated with evaporation or transpiration of moisture [2]. Compounding this effect is that the larger volume of asphalt, brick, concrete, and other materials gives urban areas a much higher thermal storage capacity than natural surfaces. One result is that large amounts of energy are stored in the urban canopy during the day and released after sunset, the

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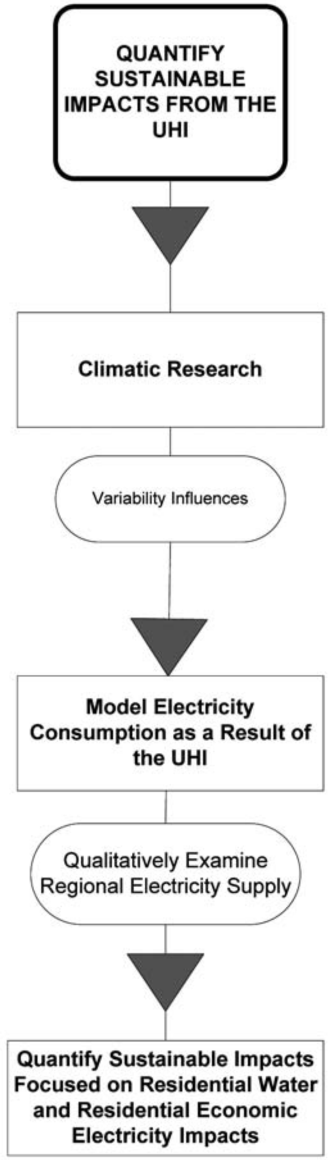
Urban Heat Island (UHI) effect. Anthropogenic sources in the urban environment generate additional heat by way of air conditioning, automobiles, and machinery. Hence, urban temperatures tend to remain relatively high into the evening hours [3,4].

In addition to anthropogenic heat, urban geometry has changed net radiation and altered convection due to slowing winds near buildings [5]. Changes in land use can also exert other kinds of climatic impacts, for example, changes in roughness length, turbulent fluxes, soil moisture, and heat budgets [6]. On an annual basis the UHI is at its maximum near the middle of the night and its minimum is in mid-afternoon. Growth of the nocturnal UHI is driven by rural cooling rates in the early evening which are much greater than the almost constant rates in the city [7]. Much of urban climatology is theory-driven, but also there are important practical engineering and policy implications which go beyond climate theory and are due to variations in social, economic and environmental conditions in a given region at a given time. This article draws on available sources of information and models and employs a logic of comparison to get a strategic assessment of the impacts of the engineered materials-induced UHI and its implications for sustainability in the rapidly urbanizing and semi-arid region of Phoenix, Arizona. International attention paid to sustainable development has occurred at a time when urban areas are gaining an estimated 67 million people per year—about 1.3 million every week. By 2030, approximately 5 billion people are expected to live in urban areas—60% of the projected global population of 8.3 billion [1]. Most of the world's future population growth will occur in arid and semi-arid regions of the world [8]. This is of significance as the need for mechanical cooling is generally greater due to the increased temperatures and limited vegetation and shade from urban forestry.

One example of the impacts of rapid urbanization and the Urban Heat Island can be observed in China which witnessed its initial production of household air conditioners in the year 1978 when no more than 223 air conditioners were manufactured. However, restricted by the capacity of production and development as well as the industrial policies of China, the total production in 1980 remained less than 20,000. In the 1990's, especially during the recent years, the industry of household air conditioners has undergone such a dramatic expansion that the total production soared to 0.22 million in 1990, to 18.2667 million in 2000 and to 23.1288 million in 2001, during which the annual increase has remained above 20%. Today, the production of air conditioners (for both domestic use and export) in China has reached one-third of the global total [9].

FIGURE 1. Organization of research conducted.



Currently, 14 of the top 20 mega cities are characterized as tropical or subtropical. The solar forcing can be extreme in these regions; especially at subtropical (higher latitude) regions where cloud cover is generally less. Heat trapping and modifying the surface energy budget is likely to have an amplified effect upon these areas [10,11].

The work provides an overview of the interdependencies of urbanization and urban climate as well as the role of engineered pavements. The research quantifies residential and regional energy usage as a resultant of the UHI through modelling and data assimilation as well as developing an assessment of the resultant water impacts (Figure 1). Therefore the research questions include: (1) what techniques can be used to quantify the UHI, (2) how has the UHI impacted electricity demand.

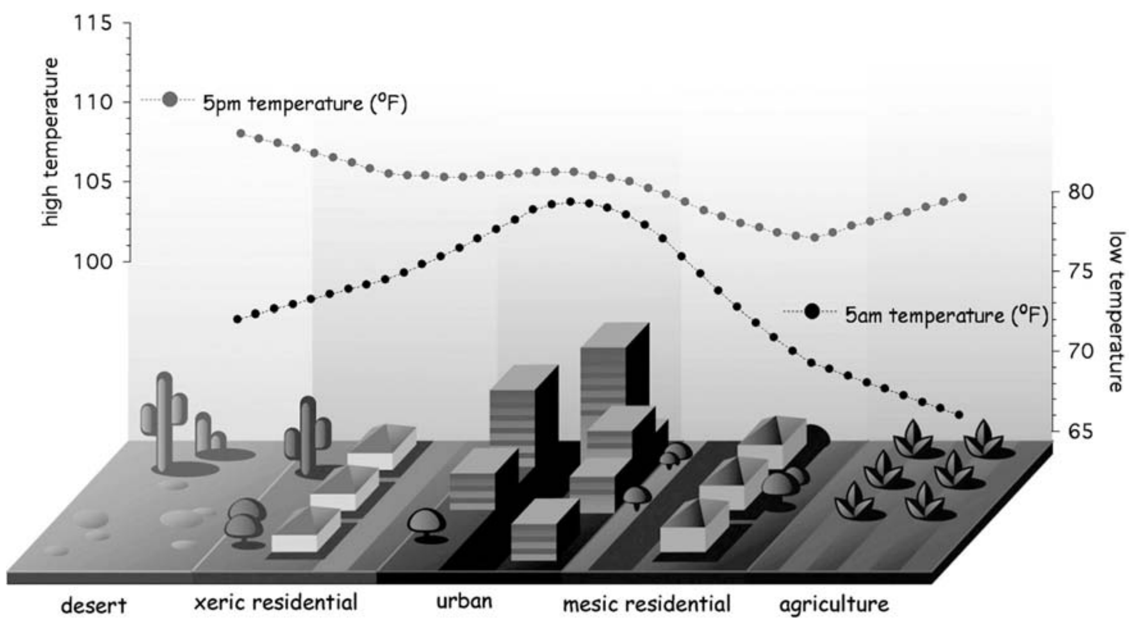
2. METHODOLOGY: ESTIMATING THE URBAN IMPACT ON TEMPERATURE

The Phoenix metropolitan area and a rural setting chosen for analysis to examine the UHI over time and the associated energy and water impacts. The semi-tropical region of Phoenix is characterized by a daytime "oasis" effect and a very strong hysteresis lag effect at night (Figure 2). Daytime temperatures in comparison to the desert rural setting in Phoenix are influenced by urbanization as well as by the addition of residential and agricultural irrigation [12]. The urban portions have a pronounced higher maximum minimum mean than the rural area ΔT_{u-r} which is the Urban Heat Island [4,13,14]. Over the 20th century, average annual temperatures in the arid subtropical Phoenix region (λ33° 26'N/φ112°W) increased 3.1°F [15]. However, the urban portions of the region have realized mean annual temperature increases of 7.6°F, a rate of three times the total region mean increase.

2.1 Site Selection

Historical climate data are used to compare and quantify the Urban Heat Island over time. A comparative evaluation of historic temperatures was undertaken through the utilization of data from the National Oceanic and Atmospheric Administration (NOAA) Western Region Climate Center.

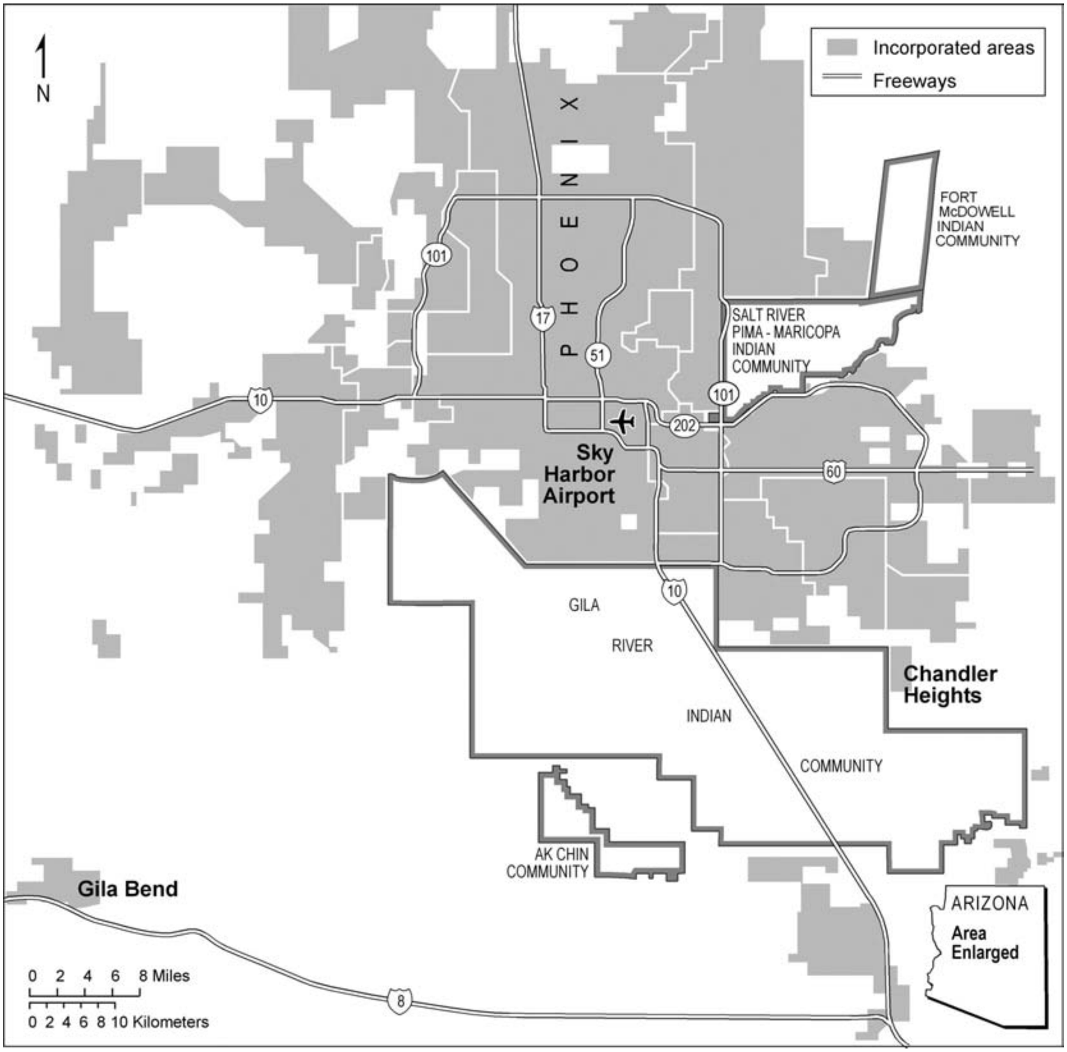
FIGURE 2. Generalized temperature profile of the Urban Heat Island phenomenon.



Techniques were developed for characterizing the UHI for an urban setting that were intended for easy use and replicability by accessing hourly records of two main airport sites in the area—Phoenix Sky Harbor International Airport within the UHI of Phoenix, and Gila Bend airport outside the metropolitan area (see Figure 3).

Thus, we tried to use data sources that are widely available such as hourly temperatures, humidity, solar radiance, wind etc, as these records are needed for calculations of the hourly cooling and heating degrees. We had to interpolate missing values for Gila Bend, as many nighttime values were missing in the record. Unfortunately, no closer hourly-recording sites to Sky Harbor were available for the time trend analysis. As explained below, we also used one year of a recent closer site to learn of issues of spatial separation especially for the variable cloudy and rainy summer monsoon period. We found that for the months of July and August, it appears that Phoenix experiences more convective activity than Gila Bend to the southwest. This may lower the actual urban effect on the cooling degree day calculations in the comparison of these two sites for annual representations. By

FIGURE 3. Regional map of Gila Bend, Chandler Heights, and Phoenix, Arizona.



using the nearby, short-term rural site near Phoenix, cooling degree days were considerably higher at the urban airport site, comparable to non-monsoon early summer differences between Phoenix and Gila Bend.

2.1.1 Urban Site: Phoenix Sky Harbor International Airport. The urban core site selected was the National Weather Service facility at Phoenix Sky Harbor International Airport (elevation 345.9m, latitude: 33° 25' 40'' N, longitude: 112° 0' 14'' W), which, is located only 3 miles from the central downtown core of the city. The airport is centrally located within the metropolitan Phoenix region. In selecting sites, airports are the most common location for historic and on-going weather collection data.

2.1.2 Rural Site: Gila Bend Airport, Arizona. The rural location selected was Gila Bend, Arizona. The primary consideration for selecting Gila Bend is that it is the only rural location with full annual climate records (i.e., daily data) since ca. 1950 and partial historic hourly climatic records since ca. 1973, which is the longest period of time for any of the rural sites evaluated.

The Gila Bend site is representative of land use characterizations of Phoenix prior to the large scale urbanization since the 1950's. The region is primarily desert with agriculture just as Phoenix had been primarily desert with agricultural land use for crops such as citrus and cotton. It is a semi-arid desert terrain with an altitude of 735 feet. Gila Bend is located 109.44 kilometers to the southwest of Phoenix and is located in Maricopa County (also the County for the greater Phoenix region). Gila Bend's population is approximately 1,747 in an area of 23.135 sq. kilometers. According to official records [16], the population has maintained a fairly steady state with a reported decrease of 7 persons in a decade (1990–2000). Evaluation of historical aerial photographs indicates minimal land use transformation during the last 40 years. Gila Bend is positioned 32.95 degrees north of the equator and 112.68 degrees west. Agriculture is the predominant industry for the area with 36,421 hectares under cultivation [16].

Conditions in the summer were critical to note relative to the respective distances between the two sites (ca. 70 miles) and the fact that the precipitation regime in summer is of a convective nature and some variability in cloud cover and rainfall could occur over these distances. Phoenix, closer to rising terrain, experiences more rainfall and likely more cloud cover during the summer monsoon. Thus, especially the months of July and August would experience differing temperature regimes as a function of the monsoon period. Our assessment indicates for other times of year that this distance factor is not as important in the comparison between the two sites.

2.1.3 Rural Site 2. Because of the spatial variability between the rural and urban sites a closer rural location was selected in relation to the Phoenix urban core. The site selected was Chandler Heights, Arizona located approximately 25 miles to the southeast of the National Weather Service Station Phoenix. However, this site has short-term climate records only, and thus we could not evaluate comparable time changes as in the comparison with Gila Bend. Thus, in the time trend assessment, we leave for now our analysis of Gila Bend vs. Phoenix, with the caveat that for the months of July and August, the UHI impacts are likely under-represented in this evaluation in seasonal and annual totals. This is verified in our very short-term comparisons of Phoenix and Chandler Heights, both sites within the Salt River Valley, but the former is urban; the latter, rural.

2.2 Results of Determining the Urban Effect on Temperatures

Table 1 summarizes the results of a linear regression analysis of time trends for the Phoenix airport and Gila Bend stations for the period 1949–2005. January, June, and Annual monthly maximum and minimum temperatures, in addition to two months during the summer monsoon—July and August were analyzed. The reason for specifically including July and August is because of the distance between Phoenix and Gila Bend (i.e., in this case Phoenix' position closer to large relief changes that promote nearby summer rains), with more summer cloudiness and rain in Phoenix likely to yield a poorer comparison for the Phoenix urban site against Gila Bend's more rural, yet distant site from moisture in the summer. Other months are less of an issue in this regard.

Both Gila Bend and Phoenix show significant trends in the minimum temperatures for all months

TABLE 1. Results of a linear regression analysis—decadal trend rates (°C) of January, June, July, August, and annual maximum and minimum temperatures. N=56 years.

Description	Gila Bend, Arizona	Phoenix, Arizona
January min temp rate	0.698C/dec*	1.141C/dec*
June min temp rate	0.465C/dec*	1.180C/dec*
July min temp rate	0.296C/dec*	0.729C/dec*
Aug min temp rate	0.472C/dec*	0.926C/dec*
Annual min temp rate	0.428C/dec*	0.984C/dec*
Jan max temp rate	0.367C/dec	0.458C/dec
June max temp rate	0.174C/dec	0.458C/dec
July max temp rate	0.026C/dec	0.283C/dec
Aug max temp rate	0.100C/dec	0.311C/dec
Annual max temp rate	0.030C/dec	0.193C/dec

(An * indicates significant correlation between year and temperature at 0.05 level of significance, using an ANOVA F-test in a linear regression calculation between year and the maximum, minimum temperatures for the particular month and the annual parameter.)

shown and for the Annual values, and the rates in Phoenix range from 1.6 to 2.5 times the trend rate of Gila Bend, indicating the major urban effect on the Phoenix temperatures. None of the rates shown for the maximum temperatures, although they are positive rates of increase, were statistically significant.

With lower temperatures and less heat storage in the urban area in January, the ratio between the trends of the two sites is lower than in summer. However, the influence of summer moisture and increased cloudiness dampens the trend in the months of July and August for both sites for both the minimum and maximum temperatures. Also, the relative ratios of the rates between the two sites drops off for July and August in comparison to June's clearer period before the onset of the monsoon. The largest difference in the trends is for the month of June. Because of the monsoon effect, our later analysis of UHI impact on cooling degree days and hours using the hourly records from these two locations must be cautiously accepted, as the results are also conditioned by moisture difference impacts on the maximum and minimum temperatures. We do have a very short term hourly record for the Chandler Heights which is presented in the electricity modeling evaluations.

3. ELECTRICITY MODELING

After historic climatic records were collected and assimilated, the next phase was to utilize the data for Phoenix to determine how cooling degree hours and heating degree hours were affected by urbanization. Cooling degree days and heating degree days set points are any variance in the daily average temperature above or below 65°F. The cooling degree days (CDD) for Phoenix are at their highest from the rural site during the months of May and June, which are characterized higher solar radiance, and by calm, clear days and nights in Phoenix. It decreases, starting at the beginning of the summer monsoon in Phoenix ca. July (183rd calendar day), in comparison to the Gila Bend site.

The Chandler Heights site shows a representative rural comparison in regards as presented in cooling degree hours and heating degree hours to Phoenix for 1999 and this is shown in Figures 4 and 5.

Cumulatively, as presented in Figure 6, since 1948 the Phoenix region heating degree hours (HDH) trend to a lower number while cooling degree hours (CDH) increase (using 75°F as the threshold). For the decade of the 1950's, the region averaged 42,264 heating degree hours per year. The Phoenix region averaged just 29,800 heating degree hours in the 1990's. Conversely, during the 1950's cooling degree hours averaged 95,597 per year and increased to 112,551 cooling degree hours per year in the 1990's.

3.1 DOE-2 MODELING

Once the cooling degree and heating degree hours were calculated, a more detailed evaluation of how the Urban Heat Island impacts electricity usage in kilowatt hours (kWh) was undertaken. Rather than rely solely on climate as a metric, the research sought to utilize electricity consumption as an additional metric to describe the Urban Heat Island and its impacts.

FIGURE 4. Phoenix cooling degree days minus Chandler Heights cooling degree days, 1999.

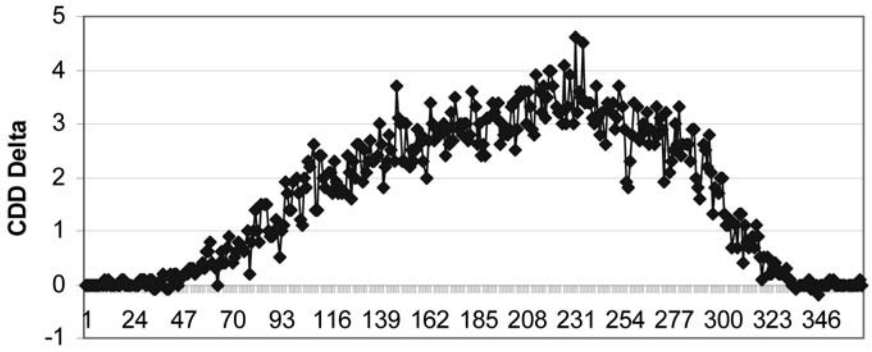
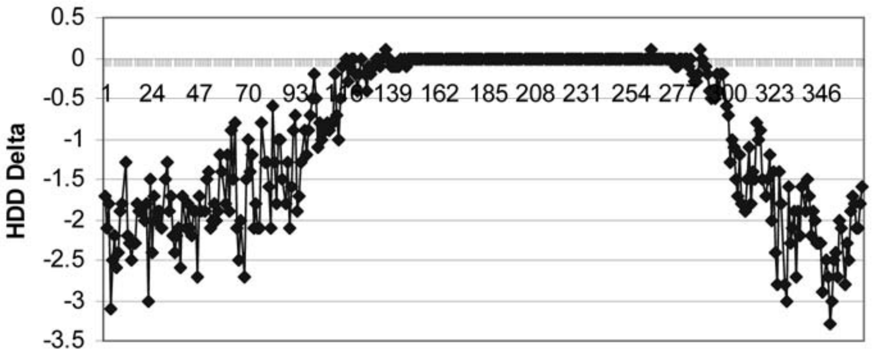


FIGURE 5. Phoenix heating degree days minus Chandler Heights heating degree days, 1999.



Because the State of Arizona is one of the most rapidly urbanizing regions in the United States it has experienced a significant increase in electricity consumption. In 1990, electricity consumption in the state was 41,500 GWh/year. This jumped to 60,000 GWh/year in 2000—a 47% change [17,18]. Examining how the Urban Heat Island contributes to electricity consumption can provide a future platform for the development of demand side management (DSM) designs which can be a part of any UHI mitigation strategy.

A single-family prototype residence was selected. It was established that modelling electricity consumption for a static residence was more representative than commercial or industrial facilities. The technologies as far as insulation, air conditioning efficiency etc., were formatted from a recent local utility (Arizona Public Service) survey for 2001 which was provided for this research. Those characteristics are presented in Table 2.

That data was then utilized to run the DOE-2 model. The US Department of Energy DOE-2 software was developed by James J. Hirsch & Associates (JJH) in collaboration with Lawrence Berkeley National Laboratory (LBNL), mostly under funding from the United States Department of Energy (USDOE). DOE-2 is a freeware building energy analysis program to predict the energy use and cost for buildings. DOE-2 uses a description of the building layout, constructions, usage, conditioning systems (lighting, HVAC, etc.), and utility rates provided by the user, along with weather data, to perform an hourly simulation of the building.

The model was run to calculate annual space cooling per kWh, annual space heating per kWh, annual HVAC fans per kWh, annual interior use per kWh, the house total annually per kWh and, HVAC total per kWh. Extracted from the modeling, HVAC kWh con-

FIGURE 6. Cooling degree hours vs. heating degree hours, Phoenix, Arizona from 1948–2002.

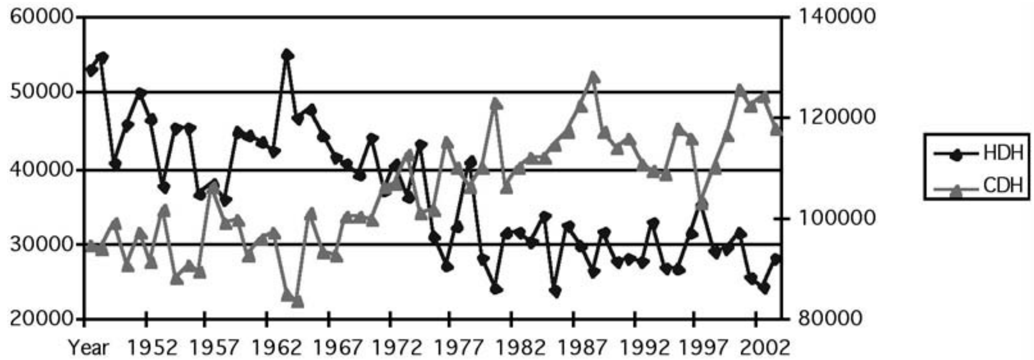


TABLE 2. Model residence characteristics used for energy simulation.

Description of input	Input values
Number of Occupants	2.6
Number of Bedrooms	4
Conditioned Area	1805 ft^2
Principal Exposures	North and South
Average Ceiling Height	9 feet
Cavity Insulation	R-11
Exterior Insulation	R-2
Roof Insulation	R-28
Glass Type	Clear single and double pane
HVAC	Heat Pump 61%
Gas Furnace	31%
Electric Furnace	8%
Size	4 Tons
SEER	9
T-stat Setpoints	79°F
Heating	71°F

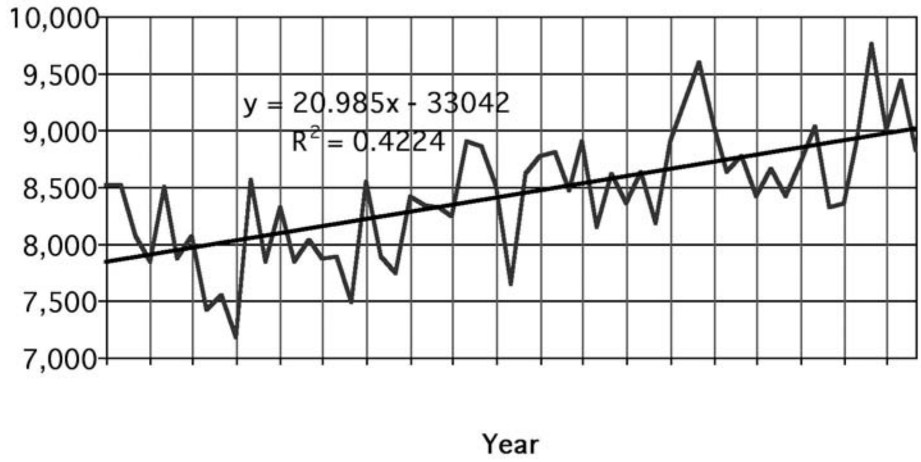
sumption based on increased cooling degree hours and the decreased heating degree hours has a net impact of overall increased energy consumption from 7,888 kWh in the decade of the 1950's to 8,706 kWh in the 1980's and currently 8,873kWh from 1994 to 2004 (Figure 7) which is consistent with prior research [19] for a small office building and an urban townhouse.

4. IMPLICATIONS FOR RESOURCE MANAGEMENT: POWER GENERATION

Once electricity consumption requirements due to the thermal modification of urban environments have been modelled, the implications for sustainable development need to be examined for the Phoenix region. As identified, electric power plants use a variety of prime movers to generate electricity [20]. The six most common prime movers [21] are:

- **Steam Turbine,** which requires a fuel source to boil water and produce steam that drives the turbine. Either the burning of fossil fuels or a nuclear reaction can be used to produce the heat and steam necessary to generate electricity. Most units are base load.
- **Gas Combustion Turbine,** which burns a combination of natural gas and distillate oil in a high-pressure chamber to produce hot gasses that are passed directly through the turbine. Most units are less than 100 MW in size and are less efficient than steam turbines. Since they have quick startup times, these units work well for peak demand and emergency demand.
- **Combined-Cycle Turbine** units utilize both steam and gas turbine prime mover technologies to increase the efficiency of the gas turbine system. After combusting natural gas in gas turbine units, the hot gases from the turbines are transported to a waste-heat recovery steam boiler where water is heated to produce steam for a second steam turbine. The steam may be produced solely by recovery of gas turbine exhaust or with additional fuel input to the steam boiler. The combined cycle turbine is used for intermediate loads.
- **Internal Combustion Engines** contain one or more cylinders in which fuel is combusted to drive a generator. These units are generally about

FIGURE 7. Simulation results for electricity consumption to cool and heat a single family residence in Phoenix, Arizona.



5 megawatts in size, and can be installed in short order for peak or emergency demand.

- **Water Turbines,** known as hydroelectric turbines, use either falling water or the force of a natural river current to spin turbines and produce electricity.
- **Other/Renewable** movers include solar, geothermal, wind, and biomass.

4.1 Arizona Power Generation

In Arizona, electricity consumption for 1999 was 58,143,730 MWh (excluding line losses), which was met by an energy generation mix comprised of 46% coal, 36% nuclear, 12% hydro, and 6% gas [22,23]. For the year 2000, Arizona in-state generation was 107,965,747 MWh (Table 3), which was met in part by 22 generation plants and regionally grid supplied electricity.

The generating capacity by fuel mix for Arizona generation (1999), as last updated by the U.S. DOE [24] indicates that the generation mix capacity is fairly balanced between fossil fuels, nuclear, and hydroelectric (Figure 8). However, actual generation (Figure 9) presents a mix heavily dependent of coal and nuclear. This can be attributed to fluctuating prices of fuel such as natural gas.

4.2 Phoenix-Area Power Supply and Demand

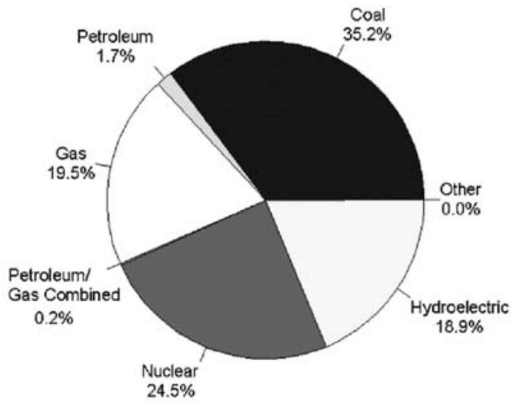
After identifying Arizona generation capacity, research was undertaken to determine the actual delivered electricity for the Phoenix region, which is comprised of a tightly integrated generation and transmission network supplied by two primary utilities: the Salt River Project (SRP) and the Arizona Public Service (APS). The area is served from four major Extra High Voltage (EHV) substations: Westing, Pinnacle Peak, Kyrene, and the Rudd substation. From these stations, 230 kV transmission lines and transformers are used to balance the Phoenix-area load, which is stepped down to 69kV transformers out of the EHV sources to the load area. The Phoenix region has a load of approximately 10,000 MW [25]. This is primarily provided by the Salt River Project (SRP) which provides 5,562 MW, and the Arizona Public Service (APS), which supplies 4,777 MW.

According to public documents from the Arizona Public Service [25], for calendar year 2002, their

TABLE 3. Arizona generation by operator, 2000 [21].

Generator Operator	Annual Generation (MWh)
Arizona Electric Power Coop Inc.	3,459,141
Arizona Public Service Co	55,149,770
CalEnergy Company Inc	440,836
Salt River Proj Ag I & P Dist	28,660,576
Snowflake Division	212,993
Tucson Electric Power Co	7,566,594
USBR-Lower Colorado Region	6,964,807
USBR-Upper Colorado Region	5,511,030
Total In-State Generation	**107,965,747**

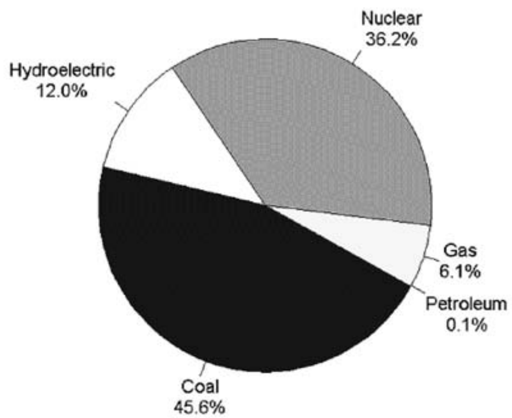
FIGURE 8. Industry generating capability in Arizona by primary energy source, 1999 [3].



peak load was 6,023 MW, of which residential portion was 2,929 MW, commercial 2,721 MW, and 373 MW classified as "other." This was met by a fuel supply which consisted of 20% gas and oil, 33% nuclear, and 47% coal.

The Salt River Project [26] estimates its electricity is derived from a 3% hydro-renewable, 5% natural gas/oil, 42 % coal, and, 14% nuclear portfolio, and 36% spot purchases [27]. However, these are published generation capacity. To validate the range of actual delivery versus generation capacity, APS Environmental Department provided actual generation

FIGURE 9. Actual industry generation by energy source in Arizona, 1999 [3].



percentages for calendar year 2003. The actual generation numbers were 56,762,425 MWh. This was met by 23.5% natural gas, 44.1% coal, 32.2% nuclear, and 0.2% renewable sources.

4.3 Economic Factors

Sustainability includes economic considerations. Based on the modeling, the economic impacts of the increased electricity demand as a result of the urban climate was calculated using 2001 average Phoenix residential electricity consumer costs of an average of $ 0.082/kWh. Based on the DOE-2 model, the average annual homeowner electricity costs by kWh for solely HVAC based on current $0.082 per kWh would result in:

- Decade of 1950's = $646.84
- Decade of 1960's = $656.13
- Decade of 1970's = $697.07
- Decade of 1980's = $713.87
- Decade of 1990's = $707.99

The climate-based kWh increase had a result of a 10% increase in the costs of cooling from the 1950's to the 1990's without being adjusted for inflation or costs of living. This also does not reflect any upgrades in technology, such as replacement of a more efficient air conditioning unit. The costs are solely based on "modern" technologies not less efficient equipment or designs from the 1950's to 2000. It is anticipated the adjusted per kWh costs per decade would be higher. However, a 10% increase in costs over a 50-year time span is not as significant in the micro-scale as are other factors which can contribute to economic impacts such as the cost of fuels, increased regulatory requirements for control technologies and increased infrastructure. All of these costs are passed on to the consumer.

4.4 Thermoelectric Power and Sustainable Water Supply

Because the Phoenix region is arid as are many of the rapidly urbanizing regions globally, the next phase of the research was to examine how residential electricity increases contribute to water consumption.

In arid regions such as the desert Southwest and in regions across the globe that are facing multi-year droughts, assured water supply and water quality are of regional importance.

What is generally unknown is that in the United States, thermoelectric power generation *withdraws* (emphasis added) more water than any other water usage, including agricultural irrigation or municipal water consumption (Table 4).

Water use in the United States, as measured by freshwater withdrawals in 1985, averaged 15 million m^3/s (338 billion gal/day) [28]. Four million m^3/s (ninety-two billion gal/day), or 27 percent of the water withdrawn, was consumed (e.g., by evaporation), and thus was not directly returned to the body of water. The remainder of the withdrawals (73 percent) was return flow available for reuse in some altered form based on the withdrawal water usage.

In 1985, freshwater withdrawals by steam-electric power plants were approximately 5.7 million m^3/s (132 billion gal/day), which was 39 percent of the total freshwater withdrawals for all use [20]. About 2.4 million m^3/s (56 billion gal/day) of saline water was used for cooling by thermoelectric plants in coastal areas. Nuclear power plants accounted for 22 percent of the total thermoelectric withdrawals and fossil-fueled plants for 78 percent.

Of the 0.4 m^3 (100 gal) withdrawn from surface waters for cooling of steam electric utilities, over 0.37 m^3 (98 gal) is returned almost immediately to the source body of water; less than 0.008 m^3 (2 gal) is consumed through evaporation [29].

The consumptive loss for once-through cooling systems [0.5 m^3/s (18 ft^3/s) per 1000 MW] is somewhat smaller than that attributed to cooling tower evaporation, which has been estimated to average 0.9 m^3/s (30 ft^3/second) per 1000 MW [30].

In those areas experiencing water availability problems such as the desert southwest, power plant water consumption may conflict with either existing or potential downstream municipal water use as well as with in-stream water uses. A shift in human population distribution and associated changes in demand for water could have important implications for the continued supply of cooling water for power generating facilities.

TABLE 4. Water withdrawals by use in the United States in 2000.

Water use	Percent
Domestic Wells	1
Livestock	1
Aquaculture	1
Mining	1
Industrial	5
Public Supply	11
Irrigation	34
Thermoelectric Power	48

4.4.1 Power Plant Water Usage. The primary use of water at power plants is for condensing steam, (i.e., cooling steam back to water). Water is also used to make up the high-pressure steam for rotating turbines to generate electricity [31].

There are a variety of estimates for water consumption including those by the Clean Air Task Force and EPRI (Figure 3-19). Water balance as a function of energy production has been estimated from 2.54 litres (0.67 gallons) of water per kWh produced via a coal-fired power plant while a natural-gas fired combined cycle power plant consumes 1.25 litres (0.33 gallons) of waters per kWh produced [17]. The National Energy Technology Laboratory [32] (NETL) operated by the United States Department of Energy estimates up to 94.64 litres (25 gallons) of water is required to produce 1 kWh of electricity from a coal plant [33,34].

A 1996 Industrial Water Survey and report [35] gathered information on the volume of water use, end uses, water treatment, and cost of water in Canada for industrial users. The survey was done under the Federal Statistics Act under an agreement between Statistics Canada and Environment Canada. The survey was mailed out to about 6,100 industrial establishments from four sectors: manufacturing, mineral extraction, thermal power, and hydro power. Their findings indicated that production of 1 kilowatt-hour of electricity requires 140 litres (36.99 gallons) of water for fossil fuel plants and 205 litres (54.16 gallons) for nuclear power plants.

According to the United States Geological Survey [35], about 408 billion gallons per day (one thousand million gallons per day, abbreviated Bgal/d) were withdrawn for all uses in the United States during 2000. Fresh ground-water withdrawals (83.3 Bgal/d) during 2000 were 14 percent more than during 1985. Fresh surface-water withdrawals for 2000 were 262 Bgal/d, varying less than 2 percent since 1985. Approximately 195 Bgal/d, or 48 percent, of all freshwater and saline-water withdrawals for 2000, were used for thermoelectric power. Most of this water was derived from surface water and used for once-through cooling at power plants. About 52 percent of fresh surface-water withdrawals and about 96 percent of saline-water withdrawals were for thermoelectric-power use. Withdrawals for thermoelectric power have been relatively stable since 1985.

As presented in Table 5, the State of Arizona water withdrawals for closed-loop cooling in 2000 were restricted to freshwater with no saline and no once-through cooling systems.

4.4.2 Implications. Based on EPRI [37] and water consumption numbers provided by the Arizona Public Service of the various water withdrawal and consumption formulas, the following Table (6) was developed to provide mean conversion factors for electricity generation and water consumption for the Phoenix region.

The numbers from Table 6 and the data presented in prior sections were then utilized to derive the actual water consumption for residential electricity generation used within the Phoenix region as presented in Table 7.

Future research is underway to quantify both the increased water consumption due to thermoelectric power needs to off-set the impacts of the urban heat island in combination with outdoor water usage required to off-set the stress of the UHI by anthropogenic and vegetative sources.

5. DISCUSSION

This article has utilized data and modeling to quantify climatic impacts as a function of land use change from urbanization and the implication of such anthropogenic forcing for energy consumption patterns in the arid southwest. The authors discuss quantifying the exact influence of the UHI as a highly diffi-

TABLE 5. Thermoelectric power water withdrawals by cooling type, 2000. All values are in million gallons per day.
State of Arizona

WITHDRAWALS FOR ONCE-THROUGH COOLING			WITHDRAWALS FOR CLOSED-LOOP COOLING						
Surface water			By source and type In million gallons per day				Total		
			Ground water	Surface water					
Fresh	Saline	Total	Fresh	Fresh	Saline	Total	Fresh	Saline	Total
0	0	0	74.3	26.2	0	26.2	100	0	100
							113 Thousand Acre Feet Per Year		

From [36].

TABLE 6. Arizona thermoelectric mean water balance.

Generation and cooling method	Water withdrawal (gal/MWh/kWh)	Estimated water consumption (gal/MWh/kWh)
Fossil/biomas steam pond cooling	500/0.5	400/0.4
Fossil/biomass cooling towers	550/0.55	500/0.5
Nuclear steam cooling towers	1,000/1.0	720/.72
Natural gas/oil combined-cycle cooling towers	230/0.23	180/.18
Natural gas/oil combined-cycle dry cooling	0	0

Data from [37,25].

TABLE 7. The Phoenix electricity = water balance for 2001 residential loads (Note: Households = 1.1M and 13,300 kWh per household).

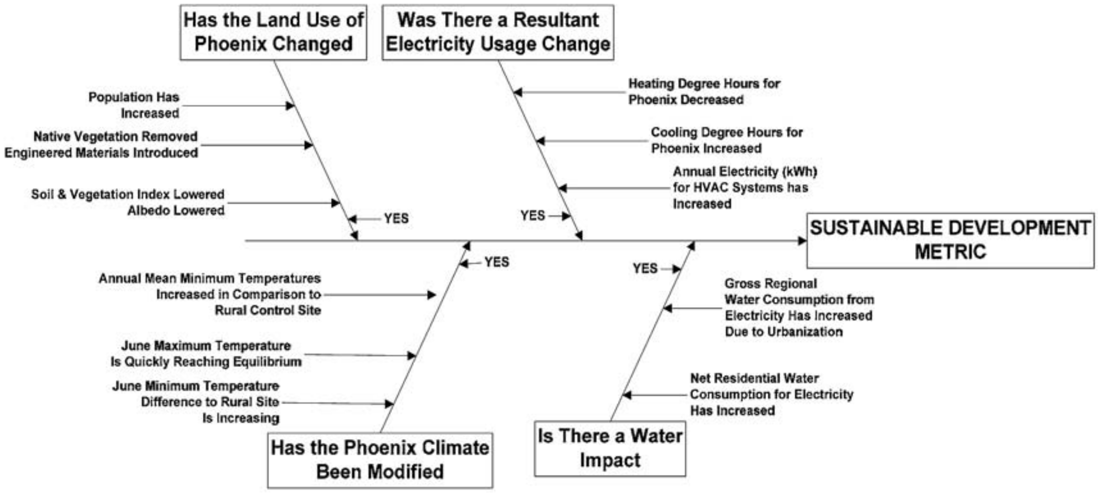
		Water withdrawals		
	Fuel mix	*Percent*	*Gallons/MWh*	*Total*
Low	Natural Gas & Oil	$0.205 \times 1.46 \times 10^7$	230	6.88×10^8
	Nuclear	$0.322 \times 1.46 \times 10^7$	1000	4.70×10^9
	Coal	$0.441 \times 1.46 \times 10^7$	525	3.38×10^9
	Renewables	$0.032 \times 1.46 \times 10^7$	0.5	2.34×10^5
			Low total	$\mathbf{8.77 \times 10^9}$
High	Natural Gas & Oil	$0.10 \times 1.46 \times 10^7$	230	3.36×10^8
	Nuclear	$0.38 \times 1.46 \times 10^7$	1000	5.55×10^9
	Coal	$0.50 \times 1.46 \times 10^7$	525	3.83×10^9
	Renewables	$0.02 \times 1.46 \times 10^7$	0.5	1.46×10^5
			High total	$\mathbf{9.72 \times 10^9}$
			Mean	$\mathbf{9.27 \times 10^9}$
			Mean acre-feet withdrawals	$\mathbf{2.84 \times 10^8}$
			Annual mean gallons per household in Phoenix	$\mathbf{8.42 \times 10^3}$
		Water consumption		
	Fuel Mix	*Percent*	*Gallons/MWh*	*Total*
Low	Natural Gas & Oil	$0.205 \times 1.46 \times 10^7$	180	5.39×10^8
	Nuclear	$0.322 \times 1.46 \times 10^7$	720	3.38×10^9
	Coal	$0.441 \times 1.46 \times 10^7$	450	2.90×10^9
	Renewables	$0.032 \times 1.46 \times 10^7$	0.5	2.34×10^5
			Low total	$\mathbf{6.82 \times 10^9}$
High	Natural Gas & Oil	$0.10 \text{ x } 1.46 \times 10^7$	180	2.63×10^8
	Nuclear	$0.38 \times 1.46 \times 10^7$	720	3.99×10^9
	Coal	$0.50 \times 1.46 \times 10^7$	450	3.29×10^9
	Renewables	$0.02 \times 1.46 \times 10^7$	0.5	1.46×10^5
			High total	$\mathbf{7.54 \times 10^9}$
			Mean	$\mathbf{7.18 \times 10^9}$
			Mean acre-feet withdrawals	$\mathbf{2.21 \times 10^4}$
			Annual mean gallons per household in Phoenix	$\mathbf{6.53 \times 10^3}$

cult process that requires statistics of global to local downscaling methods [6]. Rates of change were therefore utilized as a means to consider the various factors contributing to increased electricity demands for mechanical cooling systems.

As presented in Figure 10, the land use change and resulting UHI has an impact on microscale and mesoscale electricity consumption, which is of importance to arid and semi-arid regions such as Phoenix and other rapidly urbanizing arid regions globally.

The International Energy Outlook [18] has documented that developing countries (aka emerging economies) are projected to more than double their net electricity consumption from 4,645 billion kilowatthours in 2002 to 11,554 billion kilowatthours in 2025 in large part due to population and GDP

FIGURE 10. Sustainable engineering considerations for land use change and metropolitan infrastructure.



growth. This comes at a time of increased fuel costs and of growing awareness of the adverse impacts and contributing role that fossil fuels play in regards to global climate change. In these rapidly urbanizing regions such as China, India, and other Asian and African regions, consideration of water consumption from electricity generation and mechanical cooling demands provides another sustainable engineering factor in the on-going discussions of greater utilization of renewable energy sources. As global regions become even more urbanized and face climatic impacts such as the UHI, engineers and policy makers need to be aware of the various environmental, economic, and social impacts associated with development, including less known considerations such as water consumption from an increased need for mechanical cooling.

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