Beyond the Centralized Paradigm: Retrofitting Cities with Decentralized Energy, Transportation, and Water

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Our cities will increasingly rely on decentralized infrastructure for the collection, storage, and distribution of renewable resources (e.g. rainwater harvesting, photovoltaic micro-grids, electric autonomous vehicle hubs). Existing centralized transportation, energy, and water systems will need to be retrofitted to integrate these new decentralized system technologies. How this will occur is yet to be fully understood. To maximize benefit and minimize disruption, models for the integration of these three systems and coordinated retrofit of existing infrastructure is needed. This paper provides a replicable model for academia to join with practice and local governments to fill this knowledge gap in one mid-sized city toward future policy adoption and implementation. This paper presents three adaptive solutions of how to accomplish new sustainable infrastructure beyond the existing centralized paradigms for transportation, energy, and water.

INTRODUCTION

Our cities will increasingly rely on decentralized infrastructure for the collection, storage, and distribution of renewable resources (e.g. rainwater harvesting, photovoltaic micro-grids, and electric autonomous vehicle hubs). Existing centralized energy, transportation, and water systems will need to be retrofitted to integrate these new decentralized system technologies. Although many of these technologies have begun to be implemented within cities, how they will work with the existing centralized systems as a fully integrated solution is yet to be completely understood. To maximize benefit and minimize disruption, models for wide-spread, coordinated retrofit is needed. This paper provides a replicable model for academia to join with practice and local governments to fill this knowledge gap in the mid-sized city of Tucson, Arizona. Led through an university upper-level design studio, the project used case study, spatial mapping, quantitative analysis, and design inquiry to achieve energy, carbon, and water neutrality in 2050 through decentralized system expansion. Resource projections were used to guide speculative design solutions to provide the path to resource neutrality.

The paper begins with a discussion of the recent planning and design approaches of future-proofing and urban resilience. Literatures analyzing the current documented shifts from centralized to decentralized energy, water, and transportation systems are reviewed. Then, background on the research area of Tucson, Arizona is presented. Next, the methods are outlined with the project's quantitative and design goals. Results and presented for the three individual infrastructures. The multi-scalar and inter-system impacts are discussed. The paper concludes that by supplying a pathway to realize integrative and adaptive systems that work in tandem with the current, dominant centralized paradigm, long-term city resilience goals and resource neutrality can be achieved.

Future-Proofing Urban Energy, Water, and Transportation Networks for Toward Carbon and Water Neutrality

Faced by the future impacts of climate change, population growth, and technological innovations, cities are increasingly using the concept of future-proofing in the planning and design of infrastructure. Future-proofing is the process of anticipating future events and developing methods to minimize the effects of shocks and stresses of these events. Ultimately, the goal is to provide infrastructure that is resilient and adaptive to the effects of the shocks and stresses, particularly in climate, demographics, and technology.

There is a growing body of literature on the concept of systems resilience and its implications for urban planning and design. Two main paradigms have emerged that help shape discussions: resilience as achieving equilibrium and resilience as the ability to adapt.[1] The first paradigm defines resilience as a system's ability to return to a stable equilibrium point after disruption. The second paradigm defines resilience as the ability to adapt and adjust to changing internal or external processes – without necessitating a return to equilibrium.[2] The second approach tolerates uncertainty and "does not require a precise prediction of the future, but only some capacity to devise systems able to absorb and accommodate future events."[3] This latter definition is the one used by this paper to evaluate designs aimed at future-proofing energy, transportation, and water infrastructures.

In his seminal paper, Crawford Holling (1973) defined three critical aspects for the planning and design for this type of resilience: (1) ability to keep options open, (2) multi-scalar, and (3) heterogeneity.[4] Adding to this list, Thornbush et al. emphasizes the importance of a combined mitigation-adaptation approach, where negative effects are mitigated while adaptive solutions are implemented.[5] To accomplish these planning and design objectives, decentralized systems have been posited as an important solution.[6, 7, 8] The current, dominant urban infrastructure paradigm of centralization can be adapted through retrofitting to achieve both individual system resilience and sustainability gains across networks. However, questions persist on the impacts of this centralized-decentralized model, particularly spatial requirements[9, 10, 11] and inter-infrastructural interactions.[12] This paper seeks to address these existing questions.

Decentralized Approaches in Energy, Water, and Transportation Infrastructures

Decentralized Energy Systems

Globally, renewable energy generation and distribution through decentralized systems has received great attention due to its carbon-free production and reduction of transmission losses.[13] However, these systems face many barriers to implementation including: unavailability of manpower for maintenance, unavailability of spare parts, high cost, lack of access to credit, poor purchasing power, unfair energy pricing, lack of information or awareness, and lack of adequate training in operation and maintenance.[14] To address some of these barriers, Adil and Ko point to the importance of a sociotechnical coevolution in the integration of decentralized energy technologies into cities.[15] Beyond having the technological ability to implement, local community participation in planning and awareness of the benefits from these systems is critical to success.[16]

Decentralized Water Systems

Decentralized water systems have steadily gained traction in the areas of green infrastructure for stormwater management and alternative water harvesting (e.g. gray water, rainwater) for water scarcity. In a recent review of National Science Foundation sponsored studies and workshops on the energy-water-food nexus, Armstrong et al. point to the combined efficiencies gained in water and energy systems with decentralized approaches, particularly in the US Southwest where imported water has a high embodied energy. They summarize that urban water challenges must be addressed with a combination of enhanced water use efficiency coupled with "new materials, new technologies, and decentralized, energy-efficient unit operation that provide fit for purpose water." [17] However, barriers to such a transition persist, particularly across prohibitive and uncoordinated codes.[18] New advances in water management technology, such as sensors and in-line water quality testing, will be needed to monitor the new infrastructural configurations.[19]

Decentralized Transportation Systems

Transportation systems have important overlaps with decentralized energy and water solutions as well as new technologies (e.g. autonomous vehicles) that speak to concepts of distributed infrastructure. The growing electrification of transportation is an important contributor to urban carbon reduction as well as a potential distributed store or battery for renewable energy systems.[20] Right-of-ways in the transportation network of roads are critical areas for the integration of decentralized green infrastructure for flood mitigation. [21] Transportation system construction has shown to be a cost-effective opportunity for municipalities to bundle energy and water infrastructures and insert decentralized solutions into the existing infrastructure.[22]

Research Area

The City of Tucson sits within the United States Southwest, with ample sunshine for renewable energy generation and approximately a foot of rain each year. This climate, with few days of annual cloud cover, make it an ideal location for the expansion of renewable energy, but a challenging location for water resources. Studies have projected a more arid climate and higher risk of water shortages over the coming century for the Southwest.[23] The City of Tucson imports over 30% of its water supply from the Colorado River through a 330-mile aqueduct, the Central Arizona Project. Though this imported water prevents further drawdown of precious groundwater supplies, it has a high embodied energy and is an uncertain supply due to climate change and interstate water rights distribution. The population in the region has grown considerably in the past decades and the growth is expected to continue. In Arizona, a 25% increase is projected between the years 2012 and 2030.[24]

METHOD

The Tucson 2050 project was led by one architecture professor, sponsored by the local engineering firm of GLHN Architects and Engineers, and supported by City of Tucson and Pima County staffs. There were three main phases to the project. Methods included: case study, spatial mapping, quantitative analysis, and design inquiry.

Partnership Planning and Codification: the first third

During the first third of the project, the course and deliverables were planned and the roles between the private, public, and academic entities were clarified.

• MOU Formalization: A MOU was signed between partners and established a project budget, roles and responsibilities, and timeline for deliverables. The private partner, GLHN, contributed funding to support the dissemination of the work. City and County staffs, though officially signed cost-share letters by their department heads, contributed time in all stages for planning meetings, work with students, leading student field trips, formal reviews of student work, arranging and participating in forums for dissemination of work, and letters of support.

Research and Work Production: the second third

The second third encompassed the majority of the research and work production undertaken. The effort was orchestrated through an upper level studio comprised of eleven Bachelor of Architecture (B. Arch) students during the Spring 2018 semester (January-May).

Case Study Research: January

• Case Study of High Performing Sustainable Cities: Students researched eleven cities that had been nationally or internationally identified through public sector awards as a set of best practices for planning for carbon, energy, and water neutrality.

• Design Goal Setting: Based on the research of case studies and past Tucson plans, students set six design goals:

1) Accessibility: In 2050, downtown Tucson will be a walkable, safe, and connected area that is comprised of diverse experiences and people.

2) Equity: The aim is for downtown to foster a diverse, inclusive, educated, healthy, and thriving community under a strong economy.

3) Adaptability: 2050 Tucson will focus on resiliency and flexibility through the practice of adaptive reuse and the use of new technology.

4) Sustainability: Tucson will be net-zero energy, carbon, and water.

5) Identity: Downtown Tucson will establish a sense of place through its unique culture and regional, historically sensitive architecture.

6) Prosperity: Tucson will focus on being a human-scaled, beautiful community that supports local businesses in creating a diverse and self-sufficient downtown.

Spatial Mapping: February

• Category and Sub-Category Codification: Students divided downtown land use into eleven categories and forty-eight subcategories.

• Mapping: Students used the Geographical Information System (GIS) database of all square footage in downtown categorized into all forty-eight subcategories that was developed by a 2017 studio.

Quantitative Analysis: March

• Growth Projection: University planning faculty expert, Arthur Christopher Nelson, was engaged to devise appropriate land use growth projections – determined at 2% (2015-2030) and 3% (2030-2050). With these growth projections, students then allocated appropriate subcategory land use growth for 2030 and 2050, with added growth in categories, such as housing, that currently had a deficit.

• Resource Demand Projections: Students employed national projected energy use intensity (kWh/sf), water use intensity (gal/sf), and carbon production intensity (lb/sf) for 2030 and 2050 by subcategory to calculate downtown resource demands in the future (Table 1). New buildings and modes of transportation were given incrementally more efficient use intensities based on projections from the US Energy Information Administration's Commercial Building Energy Consumption Survey and the US Geological Survey.[25, 26] These resource intensity coefficients were based on annual resource consumption and did not include embodied energy, carbon, or water.

• Resource Supply Projections: Students used data from local weather stations (monthly precipitation and radiation) and climate change projections to calculate potential energy supply through photovoltaics and water supply from rainwater in 2030 and 2050 for the purposes of achieving net-zero energy, carbon, and water by 2050.

• Quantitative Goal Setting: Based on the students' quantitative analysis, goals for net-zero energy, carbon, and water were set for 2050, with a 50% reduction by 2030.

Design Inquiry: March and April

• Prototype Design: Students designed building and landscape prototypes (the size of a Tucson downtown city block) of the future 2050 downtown. Each prototype was analyzed through cross-cutting design strategies that addressed quantitative net-zero performance goals.

• Infrastructure Design: Students envisioned a new set of energy, water, and transportation infrastructure to achieve the net-zero goals while supporting the six design goals (Figure 1).

• Infrastructure Components: Each infrastructure selected a building-scale component to further design and render to communicate changes to the built environment at a relatable scale to the public (Figure 2).

• Day-in-the-Life Narratives: To communicate the impact of the new decentralized networks on quality of life for a broad section of the population, students developed day-in-the-life narrative for a young professional, family, and senior citizen (Figure 3). These narratives bridged the built environment with an understanding of social benefits.

Development and Dissemination: the final third

• Book Finalization: The book, Tucson 2050: a vision for a future downtown, was finalized at the end of the course. The 240 page

	2015				2050			
Category	2015 Total Sqft	Total Energy (kWh)	CO2 Energy Total (lbs)	Total Water (Gal)	2050 Total Sqft	Total Energy (kWh)	CO2 Energy Total (lbs)	Total Water (Gal)
HISTORIC	190,845	19,075,226	31,982,669	8,510,197	463,904	28,282,400	5,070,469	12,954,715
ARTS CULTURE EDUCATION	852,083	75,004,725	125,757,422	25,102,806	2,071,233	108,319,129	19,419,453	36,252,570
HOUSING	3,167,724	394,033,809	660,660,726	255,546,972	5,865,878	529,128,301	94,862,122	342,329,468
SMALL SCALE ECONOMICS	1,291,449	212,758,051	356,722,913	107,872,406	3,139,239	307,257,532	55,085,130	155,785,453
LARGE SCALE ECONOMICS	533,684	58,251,158	97,667,387	41,408,703	1,297,273	84,124,229	15,081,792	59,800,961
PUBLIC HEALTH	318,848	29,955,255	50,224,777	14,808,267	775,052	43,259,858	7,755,627	21,385,568
TRANSPORTATION MOTORIZED	740,950,529		1,323,015,895		1,801,093,600			
TRANSPORTATION NON-MOTORIZED	9,784,779				23,784,723			
OPEN SPACES	9,551,620			22,356,174	23,217,962			88,657,444
total	766,641,561	789,078,224	2,646,031,790	475,605,526	1,861,708,863	1,100,371,449	197,274,593	717,166,178

Table 1: Summary of the Energy, Water, and Carbon calculations. Image credit: 2018 ARCH 451a studio.

book was disseminated in physical copy (over 20 copies) and electronic form (since May 2018 the book has been read online over 653 times on Issuu.com) to wider public, practice, and academic communities.

• Community Engagement and Exhibition: An exhibition was held of the work with student docents in April and May 2018 in a vacant downtown retail space that was lent to the university by a private property owner. The exhibit received media coverage by local magazines, online newspapers, television interviews and radio interviews.

RESULTS: ENERGY, TRANSPORTATION (CARBON) , AND WATER

Results were measured by the achievement of the net-zero quantitative goals and six design goals. Table 1 shows the summary of base calculations for reaching the net-zero quantitative goals. Extensive calculations and forty-eight sub-categories underlie this summary table. Figure 1 registers the new infrastructures contributions to the overall net-zero energy, carbon, and water goals. On the right side of Figure 1, the bar represents total energy, carbon, or water use that needed to be reduced from the calculated 2015 baseline. The percentages show the estimated contributions to the reduction by each of the designed infrastructure implementations. The speculative design solution is comprised of five district hubs that served as the points of collection, storage, and effective micro-distribution of resources and technology. The accomplishment of the six design goals (adaptability, accessibility, equity, sustainability, identity and prosperity) were displayed in the renderings of the infrastructural networks and components (Figure 2) and day-in-the-life narratives (Figure 3). These goals were more subjective to evaluate. Results are discussed by each of the three infrastructures above.

Overall, the intent of the project was to speculate on one possible future. The work does not intent to be exhaustive, conclusive, or a singular solution. The calculations and designs made many assumptions in order to put forward this speculative scenario. The work gained publicity and public enthusiasm in the local media channels of magazines, online newspapers, television news, and radio programs. Toward future development of this work, the project secured multiyear investment from private and public partners as a result of the work. The overall project and has won awards for education (Arizona Forward's State Educator Award), design (Arizona AIA State Design Award for Regional and Urban Planning), and leadership (ACSA/AIA National Practice and Leadership Award).

Energy

The overall contributions to reach energy neutrality by 2050 from the 2015 baseline were: increase in building efficiency (10%), behavior changes (14%), adoption of a district central plant (12%), calculated space for on-site renewables (21%), estimated need expansion of off-site renewables (25%), and estimated need to purchase renewable offsets (18%) to fill the gap to neutrality (Figure 1). On-site photovoltaic installations on all (non-historic) roofs with maintenance access was assumed. A central plant and chilled water loop was implemented with a utilidor when roads were modified for autonomous vehicles. This central plant expanded an existing (but small) central plant on county property and was modeled after a successful precedent in downtown Austin. Five district hubs served as large battery storage and points of energy distribution. Two of these hubs were auxiliary central plants to the main plant.

The design goal that was most critical to presenting a vision for urban infrastructure resiliency was adaptability. Figures 3 show both the adaptability of energy infrastructure via the net network of utilidors, but also roads that are adaptable with solar collection shading that can be modified by needs over the course of a day. Figure 3 has call-outs from the potential advisory updates citizens could get from the 'smart' infrastructure throughout the day to support behavior change and overall integrated efficient resource use.

Transportation

The goal for a carbon neutral transportation system was achieved incrementally across multiple modes. Expansion of the electric streetcar, protected and shaded bicycle and pedestrian

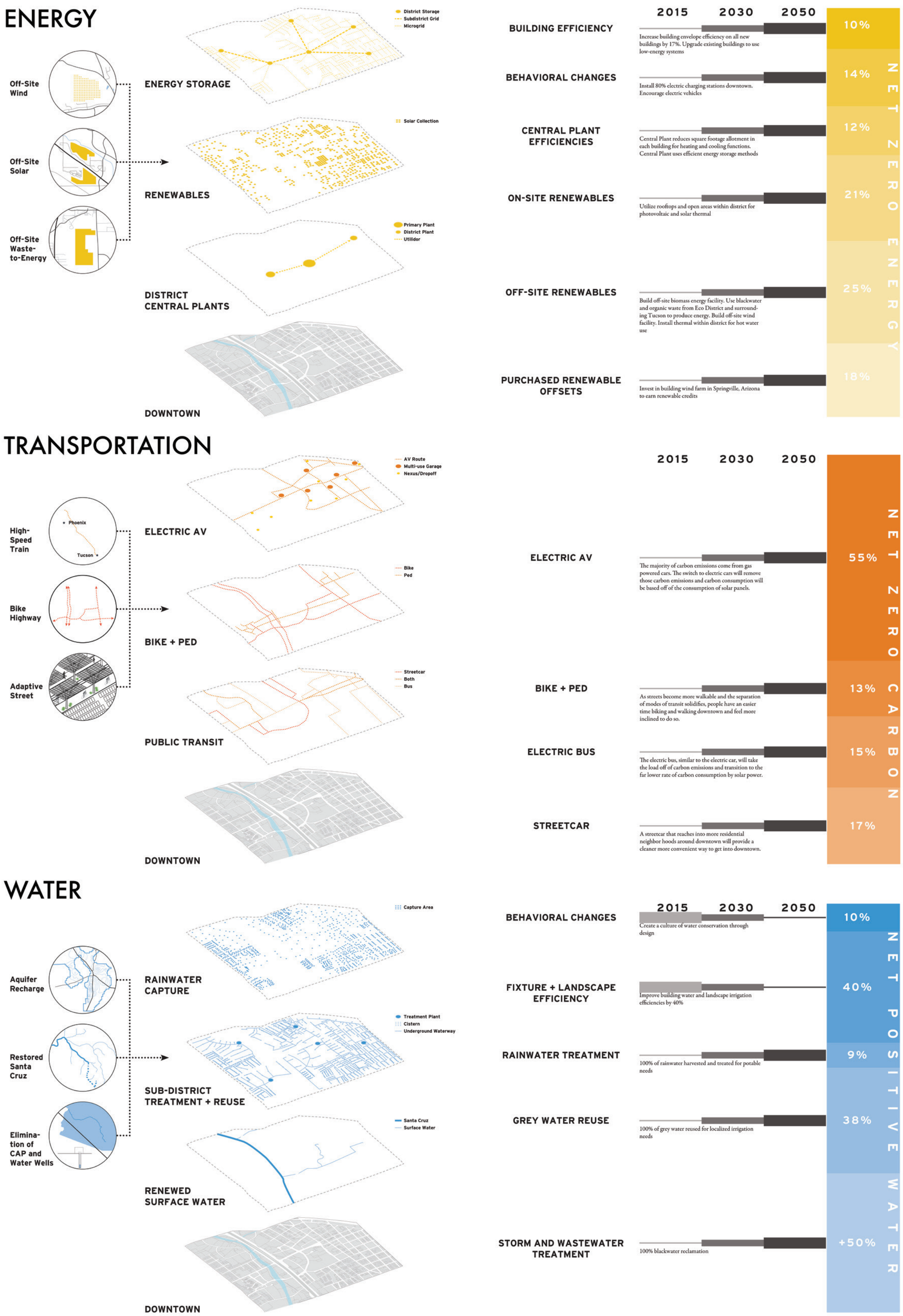

Figure 1: Master plans for energy, transportation, and water systems to reach resource neutrality in energy, carbon, and water. Image credit: 2018 ARCH 451a studio, Daniel Badillo, Eric Reynaert, Madison Neperud, Jason Sciarrotta, Ben Stewart, and Tycien Chaney.

paths, and infrastructure to support bus and car (autonomous vehicle) electrification were key. The overall contributions to reach carbon neutrality by 2050 from the 2015 baseline were: electric autonomous vehicles (55%), switch to bicycle and walking as modes of transportation (13%), bus electrification (15%), and expansion of the electric streetcar (17%) (Figure 1). The all-electric downtown transportation increased energy demands and was accounted for in the energy projections for 2050 and the net-zero calculations. Certain roads were designated for autonomous vehicles and road improvements were made for the precise track and wear caused by these vehicles with an underground utilidor to support central plant and smart city expansion. The five hubs were points for charging of the electric busses and vehicles. Smart garage conversions provided storage areas for bus and autonomous vehicles and the "nexus" hubs were collection points.

Transportation is designed to be adaptable with new hubs for multi-modal connection. For example, the Smart Garage (Figure 2) takes an existing parking garage and adapts it to meet other community needs such as storage for harvested water and urban agriculture. As private cars become a rarity in downtown due to speculative increases in autonomous vehicles and bicycling, walking, and public transportation, large amounts of parking are no longer needed. Figure 3 shows a family moving around downtown through the course of a day using the multimodal, carbon-free transportation system.

Water

The water neutrality goal was surpassed by 2050 and a net positive water district was achieved. This was made possible particularly with the use of blackwater and stormwater treatment and reuse (i.e. direct potable reuse) technology. Admittedly, these calculations failed to take losses into account (which could be as high as 15%) and may have overclaimed the reuse of stormwater (given its important ecological contributions). It is important to note that though stormwater and rainwater are harvested for use, they are eventually redistributed for localized ecological benefit and infiltration after their indoor use, thus water is not removed from the localized system. The overall contributions to reach net positive water by 2050 from the 2015 baseline were: behavior changes for conservation (10%), fixture and landscape efficiencies (40%), rainwater treatment and use (9%), gray water reuse (38%), and storm and wastewater treatment and use (+50%) (Figure 1). Rainwater capture occurred across (non-historic) roof tops in the district and was sent to the closest of five district treatment hubs, then redistributed into the potable network. Likewise, blackwater was siphoned from wastewater pipes, treated to potable quality (i.e. direct potable reuse), and reintroduced into the potable system.

The water hub in Figure 2 shows how future decentralized infrastructure doubles as points for community gathering and education. The hub is one of five throughout the district. This hub is modelled from the existing and successful Emory Water Hub. Figure 3 tracks a senior citizen through their daily interaction with the net positive system. The restored river provides an area for exercise and cooling pods that recycle rainwater provides misting and drinking water for vulnerable populations exposed to the heat in downtown.

DISCUSSION: ADAPTIVE AND RESILIENT DECENTRALIZED INFRASTRUCTURE

Thornbust et al. underscores the importance of a combined mitigation-adaptation approach when planning and designing for urban resilience.[27] This project speculated on the future of downtown Tucson in 2050 where the three systems of energy, transportation, and water were increasingly decentralized. These new multi-scalar, multi-functional, and interconnected systems achieve both the mitigation component (i.e. net-zero energy, carbon, and water) as well as adaptability (i.e. capacity to change in response to future uncertainties).

To increase urban resilience, Derrible argues for the inclusion of decentralized systems into the urban landscape through the use of Christopher Alexander's rational of semi-lattice structures (i.e. the city is not a tree).[28] In the semi-lattice structure, urban resilience is increased through the integration of systems through their natural interdependency. This project integrated across the energy-transportation, transportation-water, and water-energy nexuses. Derrible emphasizes, "Overall, a better integration of urban infrastructure can offer significant benefits to a city, and it may be time to seriously revisit our current urban infrastructure systems planning practice."[29] An argument for urban resilience was made by this speculated project when the individual decentralized systems (depicted in Figure 1) were shown to have integrated benefits for resource efficiency and social benefits (Figure 2 and 3). The interrelated or semi-lattice nature of these three decentralized systems are discussed in this section.

Energy-Transportation Nexus

Net-zero energy and carbon goals were met through integrated energy and transportation networks. Batteries distributed throughout the electrified transportation system acted as stores of energy – particularly in the plug-in autonomous vehicles that recharged during off peak energy use. Thus, pieces of the transportation system were a valuable network of modular storage units for renewable energy. Finally, although urban infrastructures normally compete for utility space, upgrades to roadways afforded opportunity to put in place utilidors for a layered system of smart monitoring and management for energy and water systems and utility expansion. Bicycle and pedestrian paths were shaded with photovoltaic panels coincident with these upgrades for overall cost efficiency.

Energy-Water Nexus

The current tightly bound relationship of energy and water (where each is required for the production of the other),

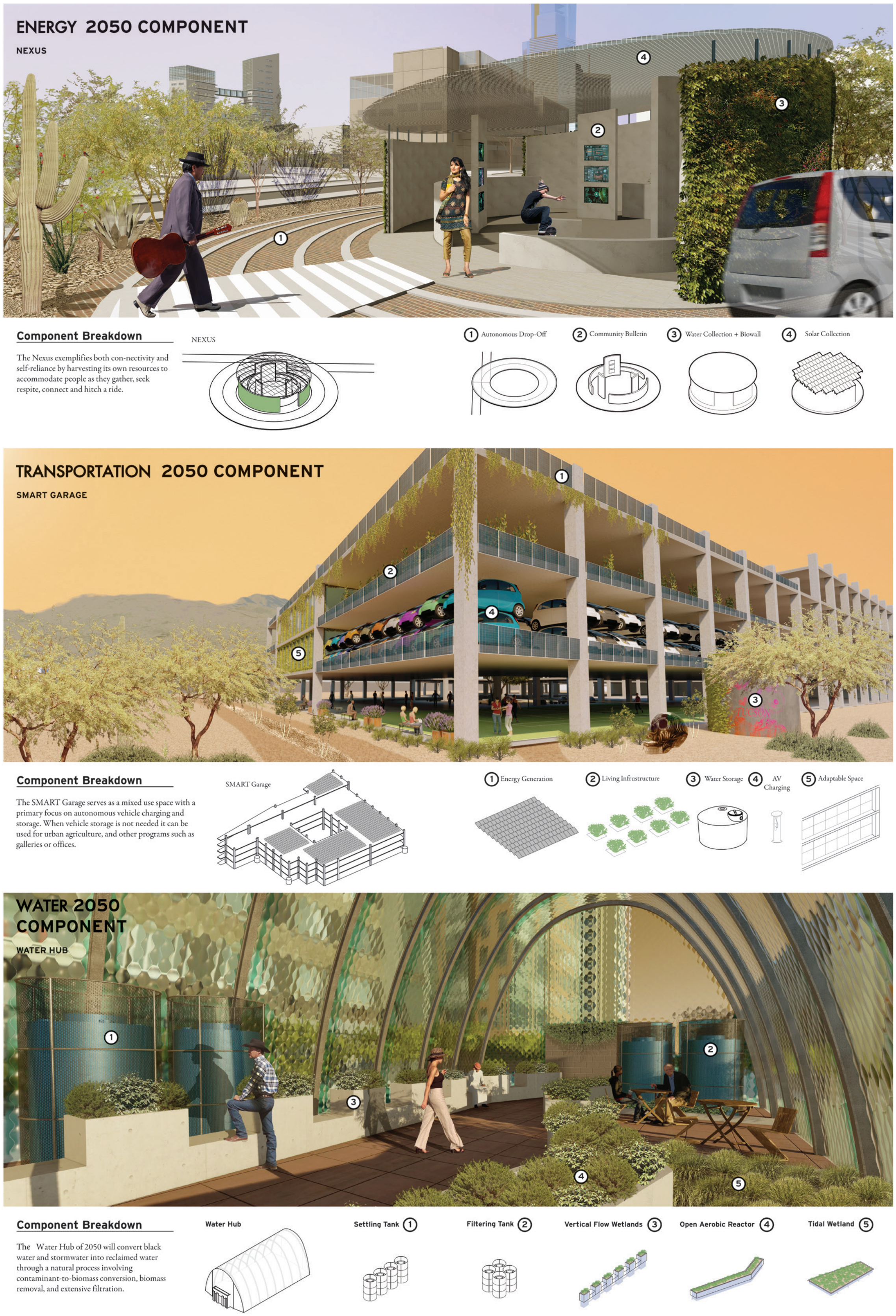

Figure 2: Renderings of building-scale components for energy, transportation, and water systems. Image credit: 2018 ARCH 451a studio, Daniel Badillo, Eric Reynaert, Ben Stewart, and Tycien Chaney.

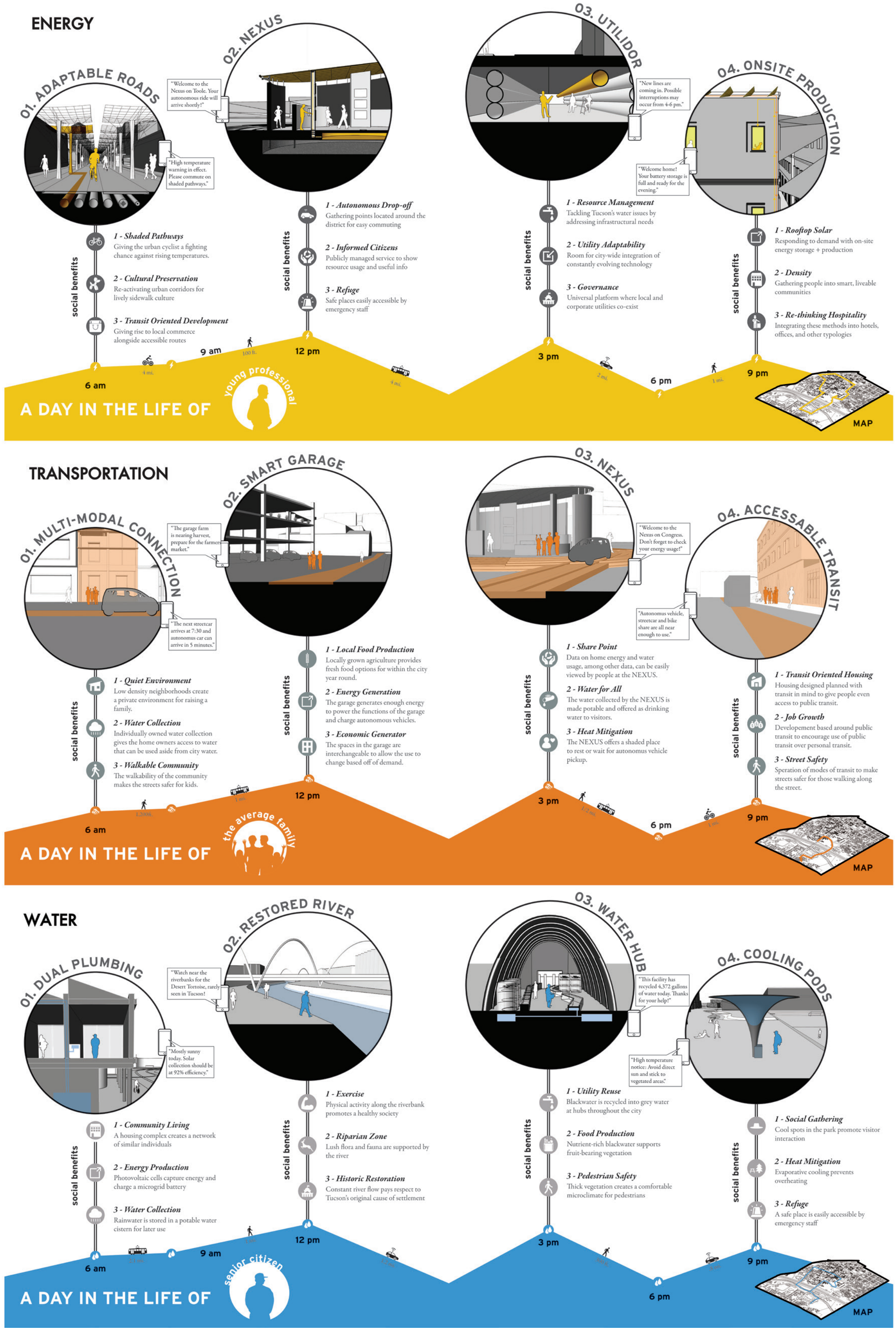

Figure 3: Day-in-the-life narratives for energy, transportation, and water systems. Image credit: 2018 ARCH 451a studio, Daniel Badillo, Eric Reynaert, Ben Stewart, and Tycien Chaney.

experienced great improvements in efficiencies by 2050. Renewable energy requires little water (only for cleaning of panels) and localized harvesting of alternative water sources require dramatically less energy than imported water. The shift to photovoltaics meant that water for energy production dramatically decreased to near zero. The shift to harvesting local water sources meant energy for water pumping dramatically decreased.

Water-Transportation Nexus

The restoration of the Santa Cruz River through the help of reclaimed water from new, adjacent decentralized treatment plants, benefited the pedestrian and bicycle networks that line either side of the river. Paths were also updated with shading structures that captured rainwater and provided treated modules of potable water for misting or drinking. The river serves as an important spine, or type of bike highway, to distribute cyclists throughout points in downtown. Finally, street parking was removed (due to the speculated uptake in autonomous vehicles), allowing for new protected and shaded bicycle lanes and green infrastructure implementation (passive water harvesting) in its place. The green infrastructure mitigated the chronic street flooding currently experienced in downtown and irrigated native trees that provide shading street-side.

CONCLUSION

New decentralized infrastructures are being incorporated into cities to expand renewable resource collection, storage, and distribution. These systems promise more resilient resource networks able to mitigate current ecological stresses and increase adaptability to future shocks. However, the multi-scalar (spatial) and multi-system (functional) consequences of this decentralized expansion on the existing centralized systems is yet to be fully understood. This project used the methods of case study, spatial mapping, quantitative analysis, and design inquiry to speculate on this future and present one possible vision and pathway to resilient energy, transportation, and water infrastructures in downtown Tucson by 2050.

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